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**AIR STRIPPING AND EMISSIONS  
CONTROL TECHNOLOGIES: FIELD  
TESTING OF COUNTERCURRENT  
PACKINGS, ROTARY AIR STRIPPING,  
CATALYTIC OXIDATION, AND  
ADSORPTION MATERIALS**

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## **EXECUTIVE SUMMARY**

### **A. OBJECTIVE**

Contamination of groundwater by volatile organic compounds (VOCs) is a serious environmental problem. Strategies for cleanup and source control of contaminated groundwater involve pumping of groundwater and treatment such that this water may be legally discharged from the site. A common technique for cleanup of groundwater contaminated with VOCs involves stripping these compounds into air. In many cases, the air is not acceptable for discharge and control of these emissions is advisable. The objective of this activity was to field test innovative air stripping with emissions control technologies. The scale of the various components used in these tests was selected such that results would be useful for better predicting the performance of application-scale equipment. The goal of these activities was to provide managers and engineers with necessary information so that decisions relating to the application of air stripping with emissions control technologies could proceed on a rational basis.

### **B. BACKGROUND**

Stripping of VOCs from groundwater utilizing air-water contactors is a well known technology. If the air from such stripping operations is sufficiently contaminated, treatment of this stream may be required to restore acceptable quality for discharge. Both packed and centrifugal air-water contactors are known to provide acceptable stripping results. Although there is a vast amount of information available in the technical literature on the design of packed towers for air stripping applications, recent studies have indicated that traditional design methods may seriously under-predict the performance of these devices at low stripping factors. Such stripping factors involving low ratios of gas to liquid flow rates are desirable when the effluent air from the stripping operation is to be further treated with emissions control devices. Although the centrifugal gas-liquid contactor has been shown to be highly efficient for air stripping, there was no rational basis for the design of this contactor available prior to the current activity. The focus of the current activity with respect to air-stripping devices was to clarify the usefulness of existing design procedures for packed towers and to provide a rational basis for the design of centrifugal contactors for air stripping service. Treatment of contaminated air is common industrial practice. Experience with the combination of air-stripping with emissions control technologies, however, was practically nonexistent prior to the current study.



### **C. SCOPE**

The technical literature relevant to air stripping with emissions control was reviewed. Test procedures were developed. Equipment for the field tests was fabricated or leased and transported to the field. The test equipment consisted of several pieces of equipment. The traditional packed tower was 0.3 meters in diameter with alternative packings consisting of 0.016-meter stainless steel Flexirings®, Koch/Sulzer Type BX plastic structured packing, Koch Flexiramic® structured packing and Delta SH structured packing from Delta Cooling Towers. The centrifugal contactor was the HIGEE unit supplied by Glitch Inc. Most of the tests with the centrifugal contactor were conducted with a porous metal packing, a typical packing for this unit; some tests were also conducted with a more open wire gauze packing. A portion of the effluent from the air strippers was routed to selected emissions control devices for testing. These emissions controls were catalytic oxidation using a test device by Englehard Corp., activated carbon adsorption, and adsorption onto selected UOP molecular sieves. Information from this study and from other sources was incorporated into an economic analysis of the key variables affecting air stripping with emissions control applications.

### **D. METHODOLOGY**

The methodology of the activity involved a determination of the state-of-the-art of technologies relevant to air stripping with emissions control and the development of useful experimentally-based improvements in the design basis for the individual technologies and for the integration of these technologies into a comprehensive system.

### **E. TEST DESCRIPTION**

The tests were oriented toward experimentally measuring the performance and other relevant information for air stripping devices and for emissions control devices under actual conditions of system operation. The experimental measurements were typically of selected jet fuel component concentrations in the influent and effluent gas and liquid streams, as well as relevant stream flow rates, temperatures, pressures, etc. These test were conducted at Eglin Air Force Base, Florida, with groundwater that had been contaminated with jet fuel components. A mobile laboratory at the site, equipped with a gas chromatograph, provided prompt analyses so that test results could be evaluated and any questionable experiments repeated in an efficient manner.

### **F. RESULTS**

Hydraulic tests for the Flexiring® packing indicated that the pressure drop was higher for groundwater than for process water; this difference was attributed to foaming of the groundwater. No significant effects on the experimental height of a transfer unit ( $H_{OL}$ ) were observed for liquid

rates ranging from 5.2 to 16.5 kg/m<sup>2</sup>-second and stripping factors (based on m-xylene) from 1.04 to 3.76. The  $H_{iOL}$  data from groundwater tests compared well with that from tests utilizing synthetic solutions made from process water. All the experimental  $H_{iOL}$  data compared very well with predictions based on the Onda correlations.

For liquid loadings of 1.4 to 16.3 kg/m<sup>2</sup>-second and stripping factors of 0.88 to 4.83, the experimental  $H_{iOL}$  for the Koch/Sulzer packing showed a strong dependence on the liquid rate and no significant effect of the stripping factor. A model for the liquid-phase mass transfer phenomena was developed; predictions of  $H_{iOL}$ , using this model coupled with existing models for gas-phase mass transfer phenomena, agreed well with the experimental  $H_{iOL}$  values. In general, the  $H_{iOL}$  values for the Koch/Sulzer packings were about 60 percent of those of the 16-mm Flexirings®. The  $H_{iOL}$  values show a strong proportionality to the liquid loading rate that is not generally observed with random packings.

For liquid loadings of 1.6 to 16.7 kg/m<sup>2</sup>-second and stripping factors (based on m-xylene) of 0.87 to 4.32, some effects of both loading and stripping factor on  $H_{iOL}$  were noted for the Koch Flexiramic® packing. A model for the liquid-phase mass-transfer phenomena was developed; predictions of  $H_{iOL}$ , using this model coupled with an existing model for the gas-phase mass transfer phenomena, agreed well with the experimental data. In general, the  $H_{iOL}$  values were similar to those using the 16-mm Flexirings®; however, the strong dependency of  $H_{iOL}$  on the liquid rate is not generally observed with random packings.

For liquid loadings of 5.3 to 27.5 kg/m<sup>2</sup>-second and at considerably higher stripping factors than had been previously used, effects of both liquid rate and stripping factor on experimental  $H_{iOL}$  values for the Delta SH packing (after correction for stripping occurring at the spray distributor) were observed.

Hydraulic test data for the centrifugal contactor indicated that the Sherwood flooding correlation underestimates the lower limit of operability for the rotational speed. In the region where the rotor speed is greater than the lower limit of operability, an empirical equation was developed for the estimation of the pressure drop. Mass transfer concepts of  $N_{iOL}$  and  $H_{iOL}$  for conventional packed towers can be adopted to the centrifugal vapor-liquid contactor by deriving the equations in polar coordinates. The equation for the  $N_{iOL}$  remains unchanged, while an area of a transfer unit ( $A_{iOL}$ ) concept is more appropriate than the  $H_{iOL}$ . The  $A_{iOL}$  appeared to be more dependent upon the specific surface area of the packing than the rotor speed and liquid flow rate under the conditions used in this study. A new correlation for predicting  $A_{iOL}$  based on the specific surface area of the packing was developed that describes the experimental data with a reasonable degree of accuracy.

The power requirement of a centrifugal vapor-liquid contactor is mainly a function of the liquid flow rate, outer radius of the packing torus, and rotor speed. A correlation based on the power required to accelerate the liquid was developed; this correlation satisfactorily predicted the power consumption at the experimental conditions. The previous claims in the literature that the centrifugal vapor-liquid contactor is not susceptible to fouling of the packing because of high shear forces were found not to be valid. Preliminary signs of plugging due to mineral deposition were observed in two of the rotors and the third rotor experienced high pressure drops due to plugging after a very short operating time.

The activity of the noble metal catalyst was lost before any useful abatement results were obtained. This loss in activity was attributed to poisoning by sulfur stripped from the groundwater. Control of emissions by activated carbon was achieved. Significant quantities of lighter hydrocarbons were noted in the stripper effluent that were not effectively adsorbed by the carbon. No generally useful results were obtained for control of emissions by molecular sieves.

Analysis of the lifetime operating costs for application of air stripping technology for remediation of contaminated groundwater indicates that (1) the use of emissions control devices for systems for air stripping of VOCs from groundwater considerably increases the costs of such operations, (2) cost considerations favor the use of lower values of the stripping factor, and (3) the costs of the remediation of contaminated groundwater are largely controlled by operating rather than capital costs.

## **G. CONCLUSIONS**

With the inclusion of the results of this study, the design basis for both packed and centrifugal air strippers appears to be adequate for application. Emissions control by adsorption of the contaminants onto activated carbon appears to be a useful technology; other potential methods of emission control will require further study and testing before their application. Economic analysis indicates that emissions control greatly increases the cost of air stripping; cost considerations favor the use of low stripping factors largely due to the impact of the stripping factor on the cost of emissions control. The overall cost of air stripping appears, however, to be largely controlled by operating rather than capital cost.

## **H. RECOMMENDATIONS**

Air strippers for VOC removal from groundwater may be designed based on existing techniques for Flexiring® packing and techniques developed in this activity for Koch/Sulzer and Koch Flexiramic® packings and the HIGEE contactor. Operational problems of precipitate accumulation and foaming of the groundwater should be considered in the design and operating procedures for air strippers.

The selection of emissions control devices for applications such as those of this study remains a troublesome issue. The failure of activated carbon to remove some unidentified hydrocarbon species in the air stripper effluent is bothersome. The rapid loss of catalytic activity would likely preclude the use of such devices for situations similar to those of this study and will require careful study for other applications. The use of molecular sieve material is desirable if field regeneration procedures are available, but will require further study for the proper selection and operation of such systems. In summary, the remaining issues for design and operation of air strippers appear to be primarily operational. Providing effective emissions control for conditions similar to those of this study will require further study.

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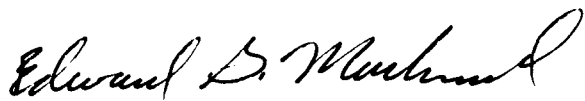
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This document details the results of activities performed under Task 4.2 of the statement of work, Phase 2: Field Test 1. A related document completed under the same contract is ESL TR 90-50, Manual for Estimating Cost of VOC Removal from Groundwater Contaminated with Jet Fuel. The AFESC/RDVW Project Officers for this effort were Captain R. A. Ashworth and Captain Edward Marchand.

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This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.



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## LIST OF ABBREVIATIONS

ALS	Automatic liquid sampler
BET	Braunauer-Emmett-Teller
BTU	British Thermal Unit
CFR	Code of Federal Regulations
CLS	Continuous liquid sampler
FIA	Flame ionization analysis
IBM	International Business Machines
LSC	Liquid sample concentration
ORNL	Oak Ridge National Laboratory
POL	Petroleum, oils, and lubricants
SAS®	Trademark of the SAS Institute, Inc.
THA	Total hydrocarbon analyzer
TIC	Temperature indicator and controller
TOC	Total organic carbon
U.S.	United States
VOC	Volatile organic compound

## LIST OF SYMBOLS\*

$A_{OL}$	Area of transfer unit, $m^2$
$a$	Gas-liquid interfacial area per unit of packed volume, $m^2/m^3$
$a_c$	Acceleration, meters/ $s^2$
$a_t$	Area of packing per unit of packed volume, $m^2/m^3$
$a_w$	Wetted area of packing per unit of packed volume, $m^2/m^3$
$C$	Correction factor for high gas rates
$C_1$	Correlation factor in equation for gas-phase mass-transfer coefficient
$D_G$	Gas-phase diffusivity, $m^2/second$
$D_L$	Liquid-phase diffusivity, $m^2/second$
$d$	Characteristic packing dimension, meter
$d_c$	Diameter of column, meters
$d_{eq}$	Equivalent diameter ( $4r_p$ ), meters
$d_p$	Diameter of packing, meters
$Fr_L$	Froude number $[(L'/\rho_L)^2 a_t / g]$
$F_s$	Parameter for correlating gas pressure drop, $(meter/second)(kg/m^3)^{0.5}$
$f_1$	$(\mu_L/\mu_w)^{0.16}$ , $\mu_w = 0.001$ N-second/ $m^2$
$f_2$	$(\rho_w/\rho_L)^{1.25}$ , $\rho_w = 1000$ $kg/m^3$
$f_3$	$(\sigma_w/\sigma)$ , $\sigma_w = 0.073$ N/meter
$g$	Acceleration due to gravity, 9.807 meters/ $s^2$
$G$	Superficial molar velocity of gas phase, $kmol/m^2$ -second
$Gr$	Grashof number, unitless
$G_v$	Volumetric gas rate, $m^3/second$
$G^*$	Gas molar rate, $kmol/second$
$G'$	Superficial gas mass velocity, $kg/m^2$ -second
$H$	Henry's constant, $m^3 atm/kmol$
$H_G$	Height of gas-phase transfer unit, meters
$H_L$	Height of liquid-phase transfer unit, meters
$\hat{H}_{OL}$	Model predicted height of overall liquid-phase transfer unit, meters
$H_{OL}$	Height of overall liquid-phase transfer unit, meters
$k_G$	Individual gas-phase mass-transfer coefficient, $kmol/m^2$ -second-atm

# **LIST OF SYMBOLS** (CONTINUED)

$k_L$	Individual liquid-phase mass-transfer coefficient, meters/second
$k_x$	Individual liquid-phase mass-transfer coefficient, kmol/m <sup>2</sup> -second (mol fraction)
$k_y$	Individual gas-phase mass-transfer coefficient kmol/m <sup>2</sup> -second-(mol fraction)
$K_x$	Overall liquid-phase mass-transfer coefficient, kmol/m <sup>2</sup> -second-(mol fraction)
$l$	Axial length, meters
$l_p$	Thickness of porous medium, meters
$L'$	Superficial mass velocity of the liquid phase, kg/m <sup>2</sup> -second
$L$	Superficial liquid molar velocity, kmol/m <sup>2</sup> -second
$L_v$	Volumetric liquid rate, m <sup>3</sup> /second
$L^*$	Liquid molar rate, kmol/second
$m$	Henry's constant (y/x)
$M_G$	Average gas molecular weight, kg/kmol
$M_L$	Average liquid molecular weight, kg/kmol
$N_A$	Mass-transfer flux of component A, kmol/m <sup>2</sup> -second
$N_{OL}$	Number of overall liquid-phase transfer units, dimensionless
$P$	Pressure, pascals
$P_e$	Power, kW
$P_T$	Total pressure, atm
$Q$	Volumetric flow rate, m <sup>3</sup> /second
$r$	Radius, meters
$R$	Ideal gas-law constant, atm m <sup>3</sup> /kmol K
$Re$	Reynolds number, unitless
$Re_L$	Liquid-phase Reynolds number ( $L'/a\mu_L$ )
$S$	Stripping factor - mG/L, dimensionless
$Sc$	Schmidt number, unitless
$Sh$	Sherwood number, unitless
$Sc_G$	Gas-phase Schmidt number ( $\mu_G/\rho_G D_G$ )
$T$	Temperature, Kelvin, K
$U_G$	Gas velocity, meter/second



# **LIST OF SYMBOLS** (CONTINUED)

$V$	Volume, $m^3$
$V_F$	Superficial fluid velocity, meters/second
$We_L$	Liquid-phase Weber number, $(L')^2/\rho_L \sigma a_t$
$x$	Mol fraction in the liquid phase, kmol/kmol
$x^*$	Equilibrium mol fraction on the liquid phase, kmol/kmol
$y$	Mol fraction in the gas phase, kmol/kmol
$Z$	Packed-bed height, meters
$Z_p$	Depth of packing per bed, meters

## **Greek Symbols**

$\alpha$	Viscous resistance coefficient, $1/m^2$
$\beta$	Inertial resistance coefficient, 1/meter
$\epsilon$	Void fraction, dimensionless
$\mu$	Viscosity, N-second/ $m^2$
$\mu_G$	Gas-phase viscosity, N-second/ $m^2$
$\mu_L$	Liquid-phase viscosity, N-second/ $m^2$
$\phi$	Correlation parameter for a given packing, meters
$\psi$	Correlation parameter for a given packing, meters
$\rho$	Density, $kg/m^3$
$\rho_G$	Gas density, $kg/m^3$
$\rho_L$	Liquid density, $kg/m^3$
$\rho_w$	Density of water, $1000\ kg/m^3$
$\sigma$	Surface tension, N/meter
$\sigma_c$	Critical surface tension of packing material, N/meter
$\sigma_w$	Surface tension of water, $0.0073\ N/meter$
$\omega$	Rotation rate, rad/second

## **Subscripts**

avg	Average
exp	experimental
G	Gas
L	Liquid

**LIST OF SYMBOLS  
(CONCLUDED)**

<b>M</b>	<b>Logarithmic average</b>
<b>p</b>	<b>Packing</b>
<b>w</b>	<b>Water</b>
<b>1</b>	<b>Bottom of tower or inside of packing torus</b>
<b>2</b>	<b>Top of tower or outside of packing torus</b>

**Legend for Figure 8**

<b>A</b>	<b>Air valve</b>
<b>C</b>	<b>Sample collection point</b>
<b>FI</b>	<b>Flow indicator</b>
<b>FX</b>	<b>Flow transmitter</b>
<b>LCV</b>	<b>Level control valve</b>
<b>LI</b>	<b>Level indicator</b>
<b>LIC</b>	<b>Level indicating controller</b>
<b>LX</b>	<b>Level transmitter</b>
<b>P</b>	<b>Pump</b>
<b>PdI</b>	<b>Differential pressure indicator</b>
<b>PdX</b>	<b>Differential pressure transmitter</b>
<b>PI</b>	<b>Pressure indicator</b>
<b>PX</b>	<b>Pressure transmitter</b>
<b>SIC</b>	<b>Speed indicating controller</b>
<b>TC</b>	<b>Temperature controller</b>
<b>TI</b>	<b>Temperature indicator</b>
<b>TIC</b>	<b>Temperature indicating controller</b>
<b>TX</b>	<b>Temperature transmitter</b>
<b>W</b>	<b>Water valve</b>

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**\*Unless otherwise specified in the text, units are as given.**

**AIR STRIPPING AND EMISSIONS CONTROL TECHNOLOGIES:  
FIELD TESTING OF COUNTERCURRENT PACKINGS, ROTARY AIR STRIPPING,  
CATALYTIC OXIDATION, AND ADSORPTION MATERIALS**

**SECTION I**

**INTRODUCTION**

**A. OBJECTIVE**

Contamination of groundwater by volatile organic compounds (VOCs) is a serious environmental problem. Sources of such contamination include accidental spills and leaking storage tanks and transport lines. Contamination of soil and groundwater from a leaking storage tank is illustrated in Figure 1. As seen in this figure, remediation of contaminated groundwater is only part of a larger problem of remediating a contaminated site which includes the unsaturated zones. The National Oil and Hazardous Substances Contingency Plan (40 CFR Part 300) identifies three general categories of remediation activities, (a) initial, (b) source control, and (c) off-site. Pumping of groundwater can be useful for all three categories. Pumping activities usually involve depressing the groundwater table in the affected region by pumping from a system of wells; the contaminated water from such an operation requires treatment as necessary for its discharge. Several technologies for cleanup of this contaminated water include air stripping, activated carbon adsorption, biological and chemical oxidation, and membrane separation.

The objective of this activity was to field test innovative air stripping with emission controls technologies for remediation of groundwater contaminated with VOCs. Air stripping involves continuous contacting of groundwater with air during which the VOCs transfer from water to the air. Control of VOC emissions in the effluent air stream from air stripping operations is currently not required in many cases, however, emissions control may be an issue in the future as regulatory pressures increase. The size of the various components used in these field tests was selected such that results would be useful for predicting the performance of application-scale equipment. The raw data from this study are available from the Chemical/Physical Treatment Technology Area Manager, HQ AFCEA/RAV, Tyndall Air Force Base, Florida 32402-6001.

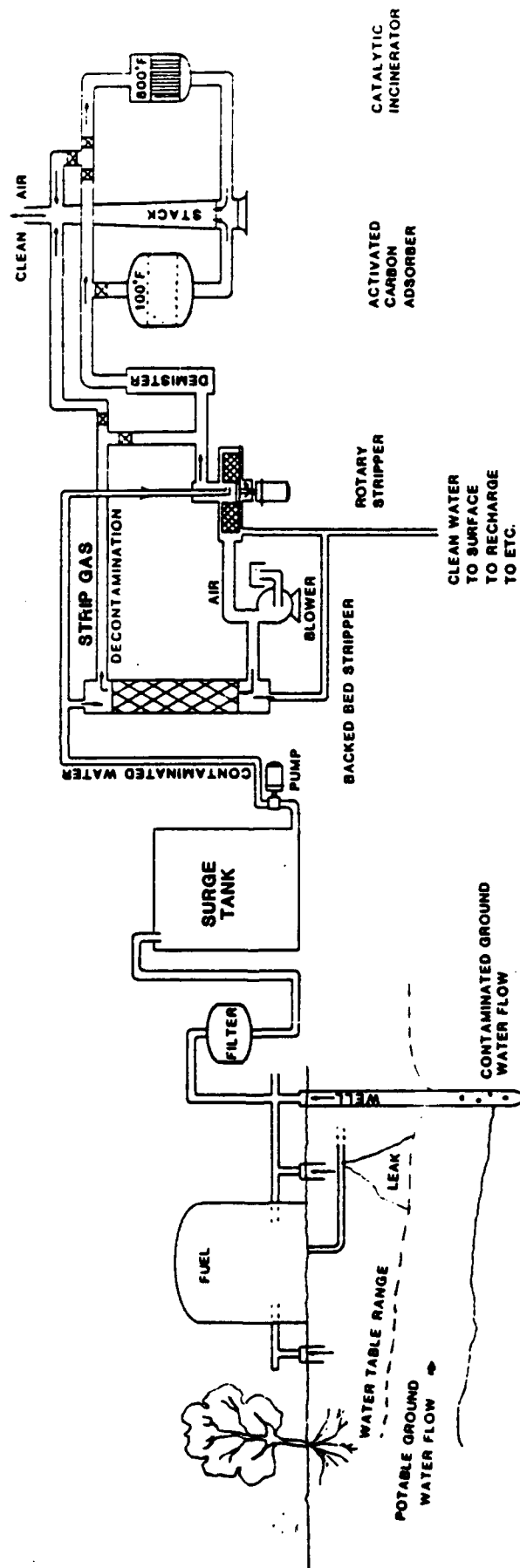


Figure 1. Subsurface Behavior of Spilled Hydrocarbons.

## B. BACKGROUND

A block diagram for the remediation of contaminated groundwater by air stripping with emission controls is presented in Figure 2. A review of relevant technology was recently presented by Singh and Counce (Reference 1). Air-water contactors can be designed to give high removal of VOCs from water; contaminants of less volatility will be removed simultaneously to a lesser extent. If the air stream from the stripper is not suitable for discharge, then treatment to restore acceptable air quality will be required. During remediation, the concentration of contaminants in the groundwater will be reduced to an acceptable level. At some point in this activity, the effluent air quality may improve to the point that any emission control originally required is no longer necessary.

Packed gas-liquid contactors, with countercurrent gas and liquid flow, provide a highly efficient means of stripping VOCs from groundwater. There is a vast amount of information on the design and operating experience for traditional packed towers. Such a tower is shown in Figure 3. Contaminated water is introduced at the top of the packing, while air flows countercurrently through the packing. The diameter of these units is chosen with consideration for the allowable pressure drop at the expected operating conditions. An alternative to the traditional packed column for countercurrent gas-liquid contact is the centrifugal contactor, a schematic of which is shown in Figure 4. The centrifugal vapor-liquid contactor is composed of two major components: the rotating packing and the stationary housing. The liquid phase is fed into the center of the rotating packing and flows outward due to the centrifugal force. After exiting the packing, the liquid phase impacts the housing wall and flows by gravity out of the unit. The vapor phase is introduced into the annular space between the packing and the housing and flows inward due to the pressure driving force. Seals are provided between the rotating packing and the housing to prevent the vapor phase from bypassing the packing. The high shear forces experienced by the liquid phase cause the formation of very thin films and rapid renewal of the interfacial surfaces. The rotation of the packing also causes considerable turbulence in the vapor phase. Both of these factors contribute to efficient mass transfer.

Two commonly used techniques for control of VOCs in air streams are activated carbon adsorption and catalytic destruction. Activated carbon has been used since the 1930s to remove VOCs from air streams, and the technology is well established (Reference 2). Organic compounds with molecular weights of over 45 and boiling points greater than 0°C are readily adsorbed onto the

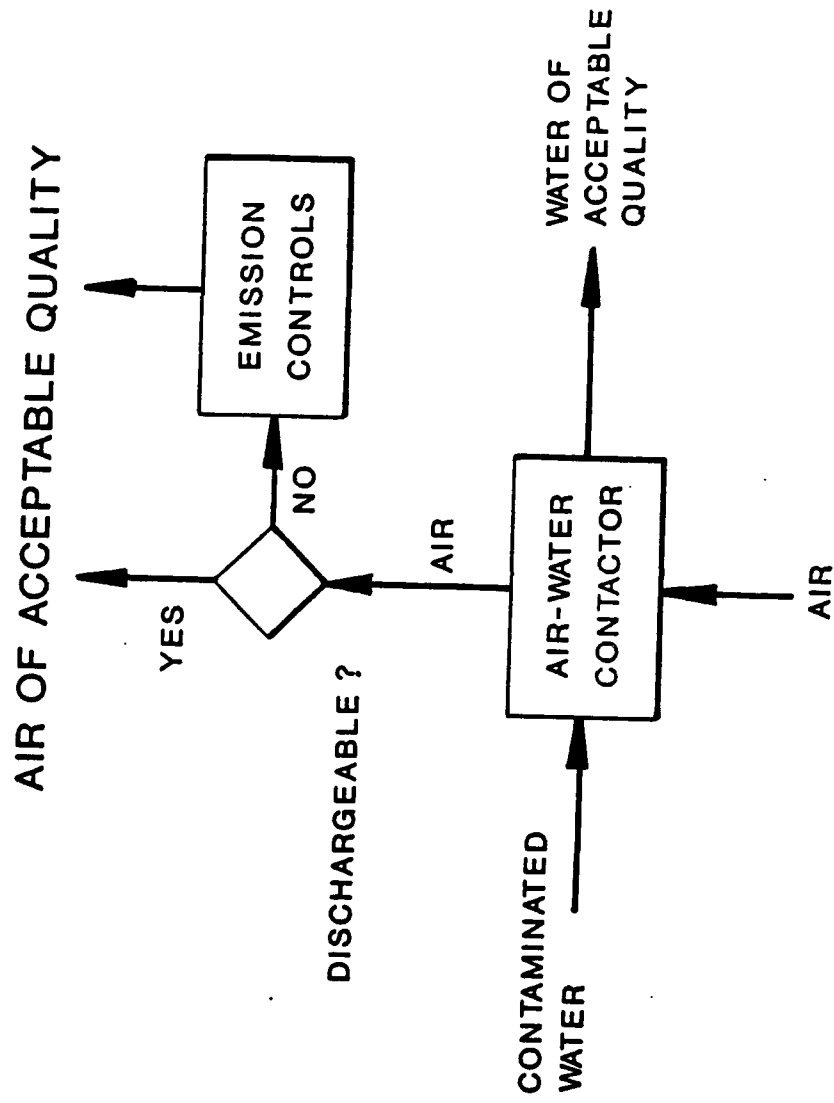


Figure 2. Block Diagram of Remediation of Contaminated Groundwater by Air Stripping with Emissions Control.

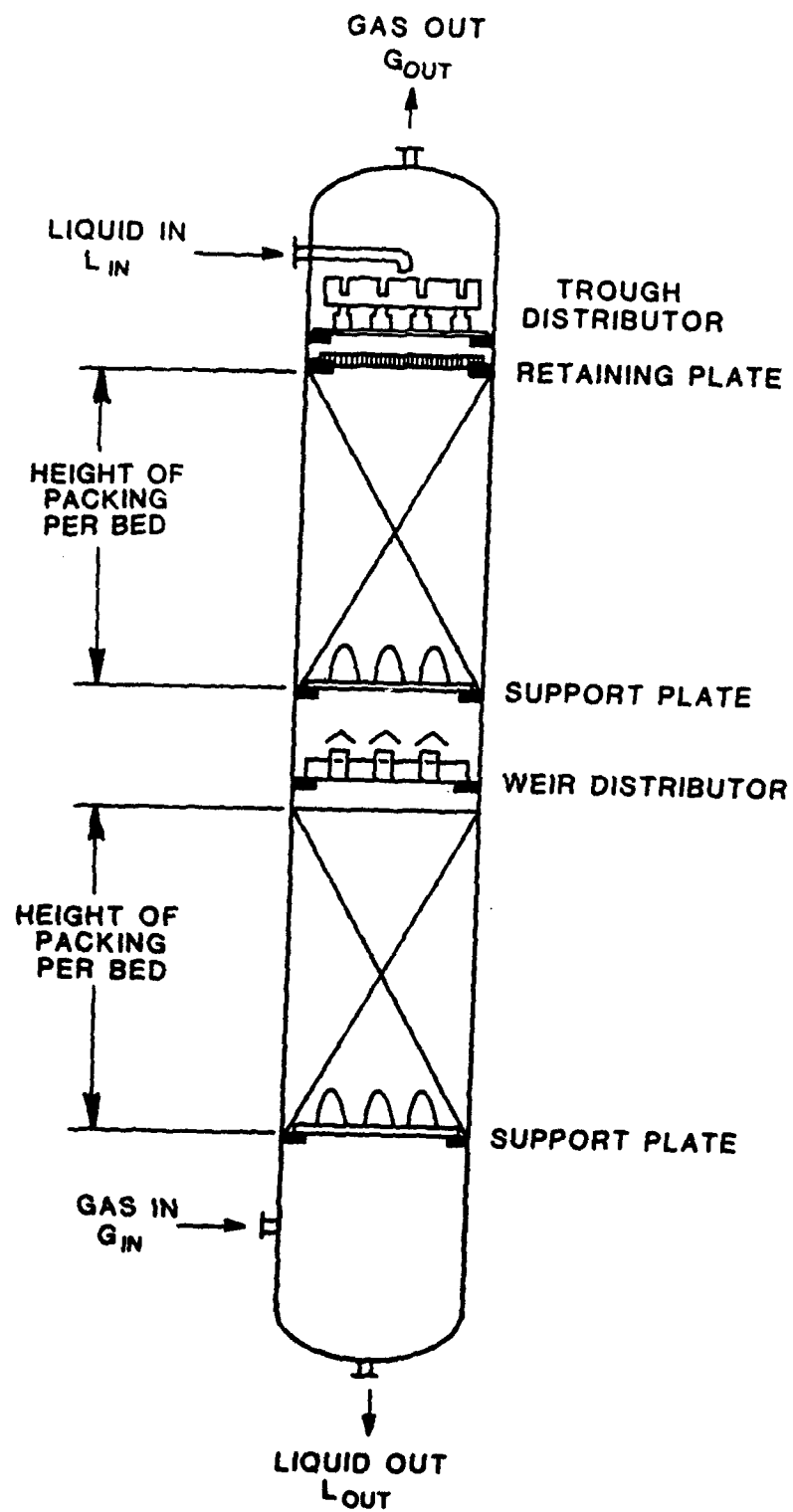


Figure 3. Typical Countercurrent Packed Tower.

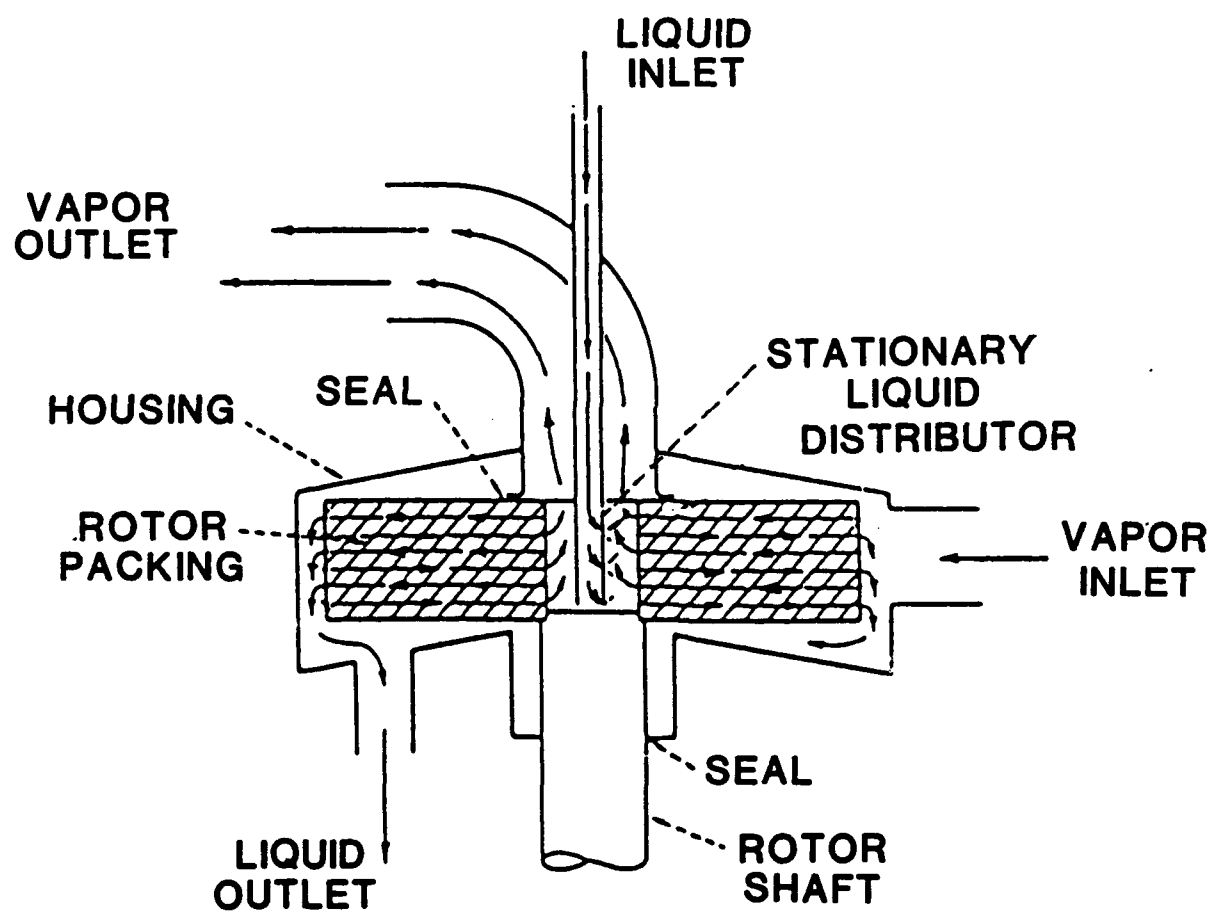


Figure 4. A Schematic of Centrifugal Vapor-Liquid Contactor.



carbon from a gas stream (Reference 3). The adsorption of the VOCs from the gas stream onto the activated carbon depends upon the type of carbon, relative humidity, temperature, concentration and type of VOC, and the regeneration step used (Reference 4). Of these variables, the relative humidity is probably of most concern in the operation of an air stripper system.

In the catalytic destruction process, a catalyst is used to promote the oxidation of VOC compounds at lower temperature than required for thermal destruction. The catalyst increases the rate of the reaction by bringing the reactants together or by lowering the activation energy of the reaction. The performance of a catalytic destruction device depends upon temperature, type and concentration of VOCs, space velocity (residence time), and the type of catalyst. Spivey et al. (Reference 5) recently reviewed the literature on heterogeneous catalytic distribution of potential environmentally hazardous compounds. Although catalytic destruction is widely used in industry to control emissions of VOCs, this technology cannot be readily extended to air stripping operations because of low concentration of VOCs in the air stream, high humidity of the air stream, wide range of contaminants, and the possible presence of mineral aerosols and poisons (Reference 6).

#### 1. Traditional Packed Tower

A common design technique for estimating the depth of packing of a traditional packed tower required for a typical application is based on the transfer unit concept (Reference 7). The required total depth of packing is expressed as

$$Z = H_{OL} N_{OL} \quad , \quad (1)$$

where the overall height of a transfer unit,  $H_{OL}$ , is the depth of packing required for one transfer unit of separation. The number of required transfer units,  $N_{OL}$ , is the change in contaminant concentration which has been normalized with respect to the average driving force.

The design of traditional packed towers is based on estimates of hydraulic and mass-transfer performance; the hydraulic performance of various packings is available from a number of sources including the manufacturer. The mass-transfer performance must be estimated based on various sources of data and is the focus of this study. The transfer unit concept for generalization of the results from the air stripping tests described in this report seems very appropriate due to its inherent simplicity and acceptance by design engineers. This concept is well established for generalization of packed tower performance. The possibility of its applicability to centrifugal contactor operation seems reasonable, based on it being a type of packed gas-liquid contactor. A schematic drawing of

a typical packed gas-liquid contactor is shown in Figure 5; in this figure the flow rates and compositions are subscripted 1 and 2 for bottom and top of packing, respectively, and may be different from those measured at top and bottom of contactor vessel. A material balance around the lower section of the contactor yields

$$Lx + G_1y_1 = L_1x_1 + Gy \quad (2)$$

Differentiating this equation yields

$$d(Lx) = d(Gy) \quad , \quad (3)$$

which represents the rate of mass transfer and may be expressed as

$$d(Lx) = N_A adZ \quad . \quad (4)$$

The mole fractions of the transferring species are expected to be dilute so that little loss of accuracy results from the assumption that the liquid and gas molar velocities are constant in contactors with constant cross-sectional area. Consideration of contactors with varying cross-sectional area, such as the centrifugal gas-liquid contactor, are addressed in later sections of this report. For dilute solutions, it is also likely that the equilibrium distribution ratio is also constant and the mass-transfer flux may be described in terms of an overall coefficient and driving force

$$N_A = K_x (x - y/m) \quad (5)$$

where  $m$  is the Henry's law constant (expressed in units of mole fraction). The overall coefficient is related to the individual phase coefficients by

$$\frac{1}{K_x} = \frac{1}{k_x} + \frac{1}{mk_y} \quad . \quad (6)$$

For air stripping of dilute concentrations from water at a constant temperature, the liquid and gas rates will remain essentially constant. The differential material balance may be related to the mass-transfer flux equation by

$$Ldx = Gdy = N_A adZ \quad . \quad (7)$$

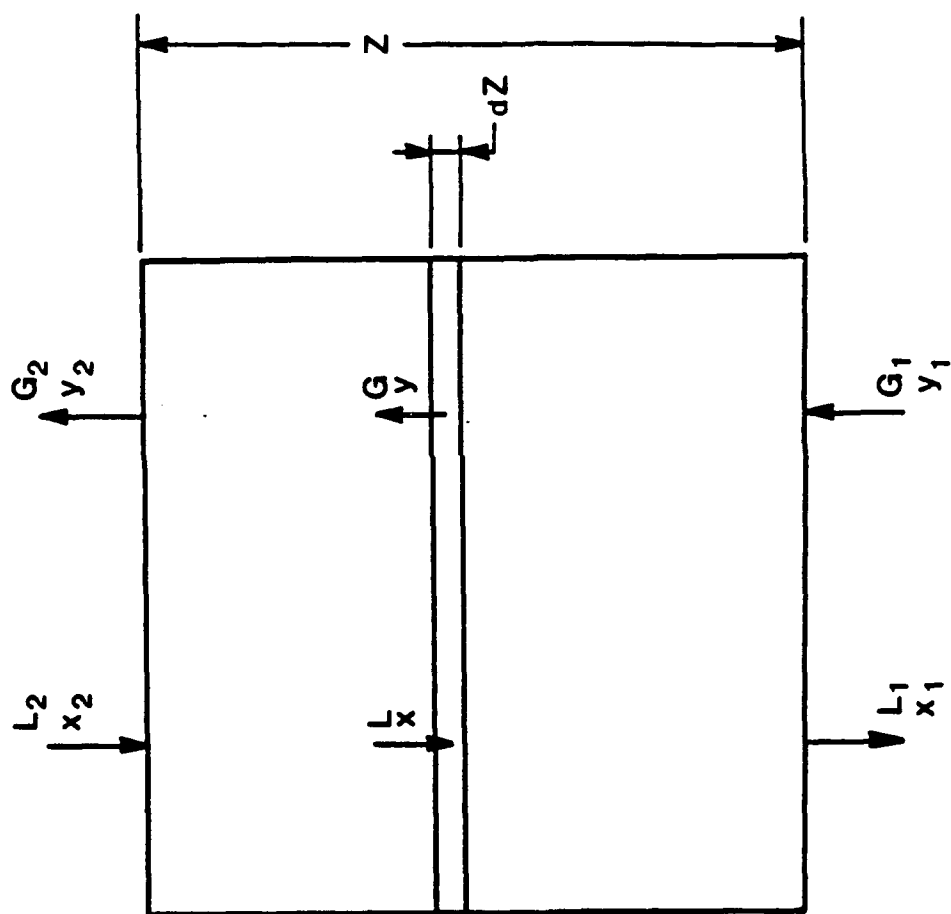


Figure 5. Schematic of Packed Gas-Liquid Contactor.

Focusing on the liquid-phase elements of this expression yields

$$Ldx = K_x a (x - y/m) dZ \quad . \quad (8)$$

Separation of variables and imposition of limits of integration yields the following

$$\int_0^Z dZ = \frac{L}{K_x a} \int_{x_1}^{x_2} \frac{dx}{x - y/m} \quad (9)$$

The expression is now in the form of

$$Z = H_{OL} N_{OL} \quad (10)$$

where  $N_{OL}$  and  $H_{OL}$  are the height and number of overall liquid-phase transfer units and may be expressed as

$$H_{OL} = L/K_x a \quad (11)$$

and

$$N_{OL} = \int_{x_1}^{x_2} \frac{dx}{x - y/m} \quad (12)$$

This equation is easily integrated (Reference 8) yielding

$$N_{OL} = \frac{x_2 - x_1}{(x - y/m)_M} \quad (13)$$

Gas-phase compositional analysis is not required;  $y$  may be found from the original material balance expression, which now incorporates the assumption of a constant ratio of liquid to gas molar velocities,

$$y = y_1 + (L/G) (x - x_1) \quad . \quad (14)$$

The expression for the number of overall liquid-phase transfer units now becomes

$$N_{\text{OL}} = \int_{x_1}^{x_2} \frac{dx}{x - y_1/m - (L/mG)(x - x_1)} \quad (15)$$

The quantity  $mG/L$  is commonly called the stripping factor and defined as

$$S = mG/L \quad (16)$$

The integrated version of this equation (Reference 9) is

$$N_{\text{OL}} = \frac{\ln \left[ \frac{x_2 - y_1/m}{x_1 - y_1/m} (1 - 1/S) + (1/S) \right]}{(1 - 1/S)} \quad (17)$$

For situations where  $y_1$  may be expected to be zero, these equations may be simplified to

$$N_{\text{OL}} = \frac{\ln \left[ \left( \frac{x_2}{x_1} \right) (1 - 1/S) + (1/S) \right]}{(1 - 1/S)} \quad (18)$$

The Henry's coefficient,  $m$ , plays an important role in determining the number of transfer units ( $N_{\text{OL}}$ ). More information on Henry's coefficient for various water pollutant may be found in a review by Singh and Counce (Reference 1). A selection of such coefficients is presented in Table 1. These coefficients are in the form of "H" type coefficients but are related to  $m$  by

$$m = y/x = H(\rho_l/M_L P_T) \quad (19)$$

The height of an overall liquid-phase transfer unit for dilute solutions of the transferring component ( $y$  &  $x \approx 0$ ) may be represented by an adaptation of Equation 6,

$$H_{\text{OL}} = H_L + H_G/S \quad (20)$$

An extensive discussion of modeling mass-transfer in packed towers is presented by Fair et al. (Reference 10). A generalized equation for the height of a liquid phase transfer unit developed by Cornell et al. (Reference 11) and refined by Bolles and Fair (Reference 12) is

TABLE 1. COMPONENT PARAMETERS FOR THE TEMPERATURE REGRESSION EQUATION

COMPONENT	TEMPERATURE REGRESSION PARAMETERS <sup>a</sup>		
	A	B	r <sup>2</sup>
nonane	-0.1847	202.1	0.013
n-hexane	25.25	7530	0.917
2-methylpentane	2.959	957.2	0.497
cyclohexane	9.141	3238	0.982
chlorobenzene	3.469	2689	0.965
1,2-dichlorobenzene	-1.518	1422	0.464
1,3-dichlorobenzene	2.882	2564	0.850
1,4-dichlorobenzene	3.373	2720	0.941
o-xylene	5.541	3220	0.966
p-xylene	6.931	3520	0.989
m-xylene	6.280	3337	0.998
propylbenzene	7.835	3681	0.997
ethylbenzene	11.92	4994	0.999
toluene	5.133	3024	0.982
benzene	5.534	3194	0.968
methyl ethylbenzene	5.557	3179	0.968
1,1-dichloroethane	5.484	3137	0.993
1,2-dichloroethane	-1.371	1522	0.878
1,1,1-trichloroethane	7.351	3399	0.998
1,1,2-trichloroethane	9.320	4843	0.968
cis-1,2-dichloroethylene	5.164	3143	0.974
trans-1,2-dichloroethylene	5.333	2964	0.985
tetrachloroethylene	10.65	4368	0.987
trichloroethylene	7.845	3702	0.998

TABLE 1. COMPONENT PARAMETERS FOR THE TEMPERATURE REGRESSION EQUATION (CONCLUDED) (REFERENCE 14)

COMPONENT	TEMPERATURE REGRESSION PARAMETERS <sup>a</sup>		
	A	B	r <sup>2</sup>
tetralin	11.83	5392	0.996
decalin	11.85	4125	0.919
vinyl chloride	6.138	2931	0.970
chloroethane	4.265	2580	0.984
hexachloroethane	3.744	2550	0.768
carbon tetrachloride	9.739	3951	0.997
1,3,5-trimethylbenzene	7.241	3628	0.962
ethylene dibromide	5.703	3876	0.928
1,1-dichloroethylene	6.123	2907	0.974
methylene chloride	8.483	4268	0.988
chloroform	11.41	5030	0.997
1,1,2,2-tetrachloroethane	1.726	2810	0.194
1,2-dichloropropane	9.843	4708	0.820
dibromochloromethane	14.62	6373	0.914
1,2,4-trichlorobenzene	7.361	4028	0.819
2,4-dimethylphenol	-16.34	-3307	0.555
1,1,2-trichlorotrifluoroethane	9.649	3243	0.932
methyl ethyl ketone	-26.32	-5214	0.797
methyl isobutyl ketone	-7.157	160.6	0.002
methyl cellosolve	-6.050	-873.8	0.023
trichlorofluoromethane	9.480	3513	0.998

<sup>a</sup>Temp regression equation:  $H = \exp(A - B/T)$ , H in atm-m<sup>3</sup>/mol, T in K.

$$H_L = \frac{\phi C}{3.28} \left( \frac{\mu_L}{\rho_L D_L} \right)^{0.5} \left( \frac{Z_p}{3.05} \right)^{0.15} \quad (21)$$

The coefficient C is designed to account for the reduction in  $H_{\text{OL}}$  as the flooding point is approached; it is a function of the ratio of the gas mass velocity to that at flooding at constant  $L'/G'$ . This coefficient may be estimated by a procedure by Coulson et al. (Reference 13) or from Figure 18.59 of Fair et al. (Reference 10). The correlation parameter  $\phi$  was adjusted by Bolles and Fair (Reference 12) to give an improved fit of a large body of data for ceramic Raschig rings and Berl saddles as well as metal Raschig rings and slotted rings such as Flexirings® and Pall Rings® and may be estimated from Figure 18.60 of Fair et al. (Reference 10). Slotted ring packings are available from a number of manufacturers; the commercial names vary, such as Pall Rings® from Norton and Flexirings® from Koch Engineering. The rings used in the tests reported here are from Koch Engineering and are referred to as Flexirings®. This equation retains Cornell's original correction factor ( $Z_p/3.05$ ); the "standard" value of  $Z_p$  used in these tests was 3.05 meters. This correction factor should only be used when the distance between liquid redistributors is over 3.05 meters.

An estimate of  $H_L$  may also be obtained using the liquid-phase mass-transfer coefficient

$$H_L = \frac{LM_L}{k_L a \rho_L} \quad (22)$$

or

$$H_L = \frac{L}{k_x a} \quad (23)$$

The mass-transfer coefficient  $k_L$  is related to  $k_x$  by

$$k_x = k_L \rho_L / M_L \quad (24)$$

In terms of film theory, these individual phase coefficients  $k_x$ ,  $k_L$ ,  $k_G$ ,  $k_y$ , etc., are those for the transfer of a component through an otherwise stagnant film. The coefficient "a" is often approximated by the use of  $a_w$  (the wetted area of packing per unit volume).

Onda et al. (Reference 15) correlated a large amount of liquid-phase transfer data to  $\pm 20$  percent by the equation



$$k_L \left( \frac{\rho_L}{\mu_L g} \right)^{1/3} = 0.0051 \left( \frac{L'}{a_w \mu_L} \right)^{2/3} \left( \frac{\mu_L}{\rho_L D_L} \right)^{0.50} (a_i d_p)^{0.4} \quad (25)$$

which is dimensionally consistent. In this equation  $a_w$  is the wetted surface of the packing obtained from

$$\frac{a_w}{a_i} = 1 - \exp \left[ -1.45 \left( \frac{\sigma_c}{\sigma} \right)^{0.75} Re_L^{0.1} Fr_L^{-0.05} We_L^{0.2} \right] \quad (26)$$

with the Reynolds, Froude, and Weber groups being dimensionless. This equation is based on experimental data for organic liquids, as well as for water. Packings included are Raschig rings, 6 to 50 mm; Berl saddles, 12 to 38 mm; 25-mm slotted rings; 12- and 25-mm spheres; and 12- and 25-mm rods. The critical surface tension of several packing materials is presented in the Reference by Fair et al. (Reference 10). The range of conditions covered by the experiments is given by

$$0.04 < Re_L < 500$$

$$1.2 \times 10^{-3} < We_L < 0.27$$

$$2.5 \times 10^{-9} < Fr_L < 1.8 \times 10^{-2}$$

$$0.3 < \frac{\sigma_c}{\sigma} < 2.$$

Generalized equations for the height of a gas-phase transfer unit developed by Cornell et al. (Reference 11) and later refined by Bolles and Fair (Reference 12) are

$$H_G = \frac{0.017 \psi d_c^{1.24} Z_p^{0.33} Sc_G^{0.5}}{(L' f_1 f_2 f_3)^{0.6}} \quad (27)$$

for ring-type packing, and

$$H_G = \frac{0.029 \psi d_c^{1.11} Z_p^{0.33} Sc_G^{0.5}}{(L' f_1 f_2 f_3)^{0.5}} \quad (28)$$

for saddle-like packing.

The correlation parameter  $\psi$  was adjusted by Bolles and Fair (Reference 12) to give an improved fit of a large body of data covering additional packing types. Values of the adjusted parameters may be obtained from Figure 18-65 of Fair et al. (Reference 10). In the use of this equation, there is the following restriction: for column diameters larger than 0.6 meters, retain the previous diameter correction for 0.6 meters (Reference 10).

An estimate of  $H_G$  may be obtained using the gas-phase mass transfer coefficient

$$H_G = \frac{G}{k_y a} \quad (29)$$

or

$$H_G = \frac{G'}{k_G a P_T M_G} \quad (30)$$

The coefficient  $k_G$  is related to  $k_y$  by

$$k_y = k_G P_T \quad (31)$$

Onda et al. (Reference 15) correlated available gas-phase absorption data with the dimensionless equation

$$\frac{k_G R T}{a_i D_G} = C_1 \left( \frac{G'}{a_i \mu_G} \right)^{0.7} \left( \frac{\mu_G}{\rho_G D_G} \right)^{1/3} (a_i d_p)^{-2.0} \quad (32)$$

where the constant  $C_1$  is 5.23 for ring and saddle packings larger than about 12 mm. For smaller packings the value of  $C_1$  is 2.00. The area term used in Equation (32) is that of the total external surface of the packing material. For desorption data, the use of the above equation and a  $C_1$  of 5.23 described most of the data fairly well. However, these tests primarily involved packings of sizes greater than 13 mm. Packings represented by the data are essentially those used previously to determine liquid-phase coefficients.

A review of methods for predicting mass-transfer coefficients and interfacial areas for, primarily, bluff-body random packings was presented by Laurent and Charpenier (Reference 16). They recommend use of the equation of Mohunta et al. (Reference 17) for  $k_L a$  predictions. They indicate that the interfacial area prediction equation of Onda et al. (Reference 15) should be accurate

to  $\pm 20$  percent except for Flexirings® where the interfacial area is underpredicted by about 50 percent. They recommend the following equation for  $k_G$  predictions with  $\pm 30$  percent accuracy:

$$\frac{k_G P_T}{G'} = \frac{C_1}{M_G} (a_i d_p)^{-1.7} \left( \frac{G' d_p}{\mu_G} \right)^{-0.3} \left( \frac{\mu_G}{\rho_G D_G} \right)^{-0.5}, \quad (33)$$

where  $C_1 = 2.3$  for packing with  $d_p$  less than 15 mm and 5.23 for  $d_p$  greater than 15 mm.

Methods for predicting mass-transfer coefficients for packed towers was also reviewed recently by Singh and Counce (Reference 1). A comparison of predicted mass-transfer coefficients from several methods with experimental mass-transfer coefficients for several modern plastic packing was made by Krotzsch (Reference 18); they confirmed that a knowledge of nominal diameter and geometrical area appear to be sufficient for estimating mass-transfer parameters. Bomio (Reference 19) presents correlations for  $H_G$  and  $H_L$  for the Koch/Sulzer type BX plastic packing; the data appear to be primarily gas-phase resistance controlling so that the  $H_L$  predictions are likely to be more qualitative than the  $H_G$  prediction. Some recent work involving predictions of mass coefficients for several modern packings by Mahajani and Joshi should be available soon in the open literature.

A disturbing observation was, however, recently noted by Harriott (Reference 20). Harriott noted an unexpected increase in  $H_{OL}$  as the stripping factor decreased to unity and beyond.

Harriott concluded that this increase in  $H_{OL}$  was due to inherent liquid maldistribution in randomly packed beds and found that the ratio of the experimental to calculated  $H_{OL}$  was inversely proportional to  $S^2$ , as expressed by

$$(H_{OL})_{exp} / H_{OL} = 1 + 0.9/S^2, \quad (34)$$

for a range of  $S$  of approximately 0.8 to 5.

## 2. Rotary Contactor

The "HIGEE" centrifugal contactor (Glitsch Inc., Dallas, Texas) has been used in the chemical industry to remove hydrogen sulfide from natural gas by use of a suitable amine (Reference 21). There has been only one test where a centrifugal contactor was used for air stripping of volatile organics from groundwater (Reference 22); this test was conducted at a United States Coast Guard air station in East Bay Township, Michigan, to remove benzene, toluene, xylenes, trichloroethylene, 1,2-dichloroethane, and tetrachloroethylene from groundwater. Removal efficiencies of greater than 99 percent were achieved for all the contaminants, except for 1,2-

dichloroethylene, at a gas-to-liquid ratio of 30:1 and rotor speed of 435 rpm. Other qualitative observations from this study included: (1) at constant air-to-water ratios, an increase in the rotational speed of the rotor above 700 rpm was found to increase the removal efficiency only slightly and (2) an increase in the air-to-water ratio above 40:1 (volume/volume) produced little effect on the removal efficiency at constant rotor speed. Little quantitative mass transfer information was obtained in these tests due to the high removal efficiencies. Although no major problems were encountered in the operation of the rotary air stripper, entrainment of the water in the air effluent stream was reported to be significant.

The concepts used to design conventional packed columns can be modified for the design of the centrifugal vapor-liquid contactors. In designing a conventional packed column, the diameter of the column and the depth of packing are the two variables which need to be determined. Similarly, for the centrifugal vapor-liquid contactor the cross-sectional area at the inner radius and the outer radius are the two critical variables. An additional complexity arises in the design of the centrifugal vapor-liquid contactor because the cross-sectional area at the inner radius can be varied by changing either the radius or the axial length. This results in an iterative design process in which the inner and outer radii and the axial length are varied to arrive at an optimum design solution.

The cross-sectional area required at the inner radius is dependent upon the hydraulic capacity required. Munjal (Reference 23) presented data which indicate that the Sherwood flooding correlation may be used to determine the cross-sectional area at the inner radius. The data presented are, however, for a single type of packing and, consequently, hydraulic tests with other packing are desirable to further validate the application of the Sherwood flooding correlation.

Two empirical correlations which might be used to estimate the mass-transfer coefficient have been proposed in the literature. Both of these empirical correlations are based on the penetration model. The first correlation is that proposed by Tung and Mah (Reference 24):

$$\frac{k_L d}{D_L} = 0.96 Sc^{1/2} Re^{1/3} \left( \frac{a_t}{a_w} \right)^{1/3} \left( \frac{d^3 \rho_L^2 g}{\mu_L^2} \right)^{1/6}, \quad (35)$$

and the second one is that used by Vivian et al. (Reference 25):

$$\frac{k_L a d^2}{D_L} = 0.023 Sc^{1/2} Gr^{0.38} \left( \frac{dL'}{\mu_L} \right)^{1/2} \left[ 1 - 1.02 \exp \left( - (0.15) \left( \frac{dL'}{\mu_L} \right)^{0.4} \right) \right] \quad (36)$$

Notice that this equation, unlike that used by Tung and Mah, does not require knowledge of the interfacial area.

The accuracy of these correlations for the design of a centrifugal vapor-liquid contactor is unknown because the data needed to establish their validity was previously not available.

The uniqueness of the chemical characteristics of the groundwater for each application presents an uncontrolled element in the design process. Iron is commonly found in groundwater. When exposed to air, oxidation and subsequent precipitation of the insoluble species in the column increases the operating cost of such units and produces yet another waste stream for disposal. Both the traditional packed column and the centrifugal contactor are susceptible to becoming plugged with precipitate material. Groundwater has also been observed to foam due to the presence of natural surfactants. Such foaming can have deleterious effects on mass transfer and hydrodynamic performance of packed stripper towers. Foaming in packed columns can cause a reduction in the useful range of operating conditions. Foaming is less likely to be a problem in centrifugal contactors due to the high centrifugal forces which tend to cause phase separation. Biological growth in traditional packed stripper towers has also been observed to present severe performance constraints (Reference 26).

### 3. Emission Controls

A portion of this activity focused on the control of the VOC compounds in the effluent air from the strippers. The three control measures studied were catalytic incineration, adsorption by activated carbon, and adsorption by molecular sieves. The hydraulic performance of these devices is generally available from the manufacturer and other literature sources. The VOC removal characteristics of these devices was the focus of this activity. The performance of the catalytic incinerator is characterized by a simple component and total hydrocarbon removal efficiency. The performance of the activated carbon and molecular sieves is characterized by determining the loading capacity of the adsorbent when near fully utilized; this point of near utilization is sometimes referred to as "breakthrough."

### **C. SCOPE/APPROACH**

This report describes field experimentation and demonstration of equipment for air stripping of VOC compounds from groundwater and control of gaseous emissions. The type of equipment and components were chosen because they represented the best choice for anticipated field operation and application. The scale of equipment was chosen as to be useful for any future scale-up activities. The test conditions were selected to demonstrate or acquire data in areas where performance was uncertain or data for scale-up lacking. The experimental results were incorporated into easy-to-use design correlations and other text information.

## SECTION II

### PREDICTIVE METHODS

This section presents the methodology for analysis of the experimental data from this activity. Where these analysis techniques were developed as a part of this activity, more details are provided.

#### A. CONVENTIONAL PACKED TOWER

Two types of packing were used in the packed-tower air stripping tests — dumped packing and structured. The use of dumped packing allowed intermediate liquid sampling in the packed section while the monolithic nature of the structured packing prevented sampling within the packed section of the tower.

##### 1. Conventional Packed Tower with Dumped Packing

The analysis of data from tests with the dumped packing is based on a version of Equation 1

$$H_{iOL} = Z/N_{iOL} \quad (37)$$

The values of  $Z$  represent the distance between two sampling locations and is calculated by

$$Z = Z_j - Z_i \quad (38)$$

where  $j$  is greater than  $i$ .

The values of  $N_{iOL}$  represent the number of transfer units for the section of packing defined by Equation (38) and is calculated by a version of Equation (17)

$$N_{iOL} = \frac{\ln \left[ \frac{x_j - y_i/m}{x_i - y_j/m} \right] (1 - 1/S) + 1/S}{(1 - 1/S)} \quad (39)$$

The value of  $y_1$  (at the entrance to the packing) is estimated by

$$y_1 = L/G (x_1 - x_{out}) \quad (40)$$

By taking all possible  $j$  and  $i$  combinations into account [subject to the constraint of Equation (38)] a number of  $Z$  and  $N_{iOL}$  values may be generated and  $H_{iOL}$  determined by the slope,  $\Delta Z/\Delta N_{iOL}$ .

## 2. Conventional Packed Tower with Structured Packing

Since the structured packing is supplied in monolith cylinders, sampling within the packed section was thought not to be desirable. The  $N_{OL}$  values were obtained for these cases by use of Equation (17)

$$N_{OL} = \frac{\ln \left[ \frac{x_2 - y_1/m}{x_1 - y_1/m} (1 - 1/S) + (1/S) \right]}{(1 - 1/S)} \quad (41)$$

and  $H_{OL}$  obtained by a rearrangement of Equation (1)

$$H_{OL} = Z/N_{OL} \quad (42)$$

Since reliable information on  $H_G$  is available in the literature, the value of  $H_L$  may be estimated using a rearrangement of Equation (20)

$$H_L = H_{OL} - H_G/S \quad (43)$$

## B. CENTRIFUGAL CONTACTOR

The concepts used to design conventional packed columns can be modified for the design of the centrifugal vapor-liquid contactors.

### 1. Mass Transfer

The equation needed to calculate the outer radius of the packing torus can be derived using the transfer unit concept from conventional packed column design, which was discussed previously. Using the schematic of the packing torus shown in Figure 6, a material balance can be written for a differential volume of the packing. At steady state, the material balance equation for the liquid phase,

$$-L^* dx = K_x a (x - y/m) dV = k_x a (x - x^*) dV \quad (44)$$

The differential volume can be written in terms of the radius as:

$$dV = 2\pi l r dr \quad (45)$$

where  $l$  is the axial length of the packing. Substitution of Equation (45) into Equation (44) and subsequent rearrangement and integration gives:



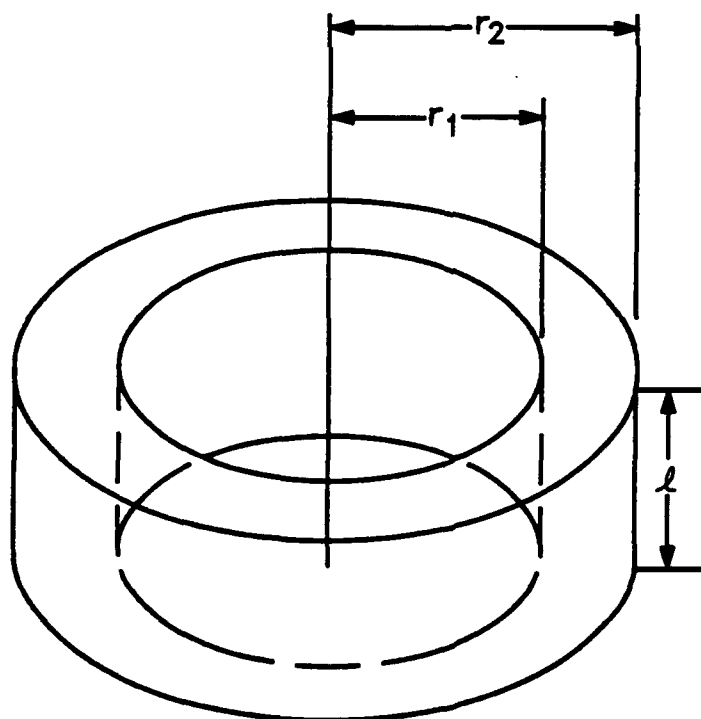
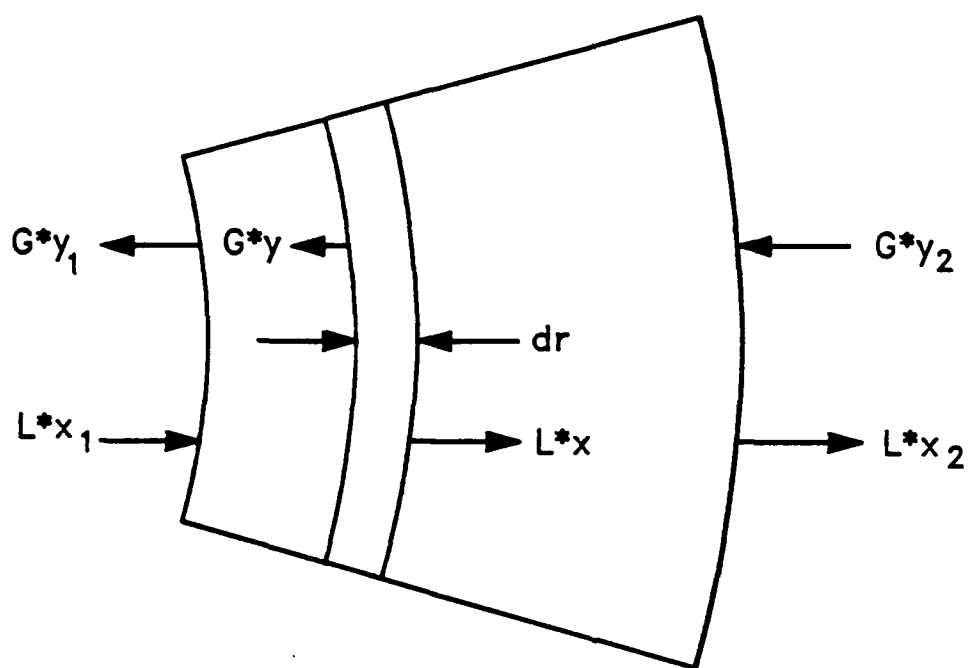


Figure 6. Differential Volume Element for the Packing Torus.

$$\frac{-L^*}{lK_x a} \int_{x_1}^{x_2} \frac{dx}{x - x^*} = 2\pi \int_{r_1}^{r_2} r dr \quad (46)$$

where  $x_1$  and  $x_2$  are mole fractions, in the inlet and outlet streams, respectively, to the rotor.

Incorporating the negative sign into the integral on the left hand side yields:

$$\frac{L^*}{lK_x a} \int_{x_2}^{x_1} \frac{dx}{(x - x^*)} = \pi (r_2^2 - r_1^2) \quad (47)$$

The equation is in a form similar to that used for conventional packed columns. The main difference is that the right hand side is an area instead of a height. Since the overall  $H_{\text{tol}}$  term used in design of conventional towers is not appropriate in polar coordinates, an overall area of transfer unit ( $A_{\text{tol}}$ ) expression is used and is written as:

$$A_{\text{tol}} = \frac{L^*}{lK_x a} \quad (48)$$

$N_{\text{tol}}$  characterizes the difficulty of removing the VOCs from the groundwater and is independent of the coordinate system. The  $N_{\text{tol}}$  was defined in Equation (17) utilizing concentration information at the inside and outside rotor surfaces.

Equation (47), the basic mass-transfer performance equation for centrifugal contactors, may now be expressed as

$$A_{\text{tol}} N_{\text{tol}} = \pi (r_2^2 - r_1^2) \quad (49)$$

## 2. Hydraulic Performance

The hydraulic operating envelope of a centrifugal vapor-liquid contactor has two boundaries, as shown in Figure 7. The upper boundary arises from the design and is purely mechanical. This boundary is the maximum operating speed of the particular machine. Once the machine is designed and fabricated, this boundary is difficult to change without significant modifications to the unit. The lower boundary, on the other hand, depends upon the operating conditions. It is this boundary which was investigated in the hydraulic tests.

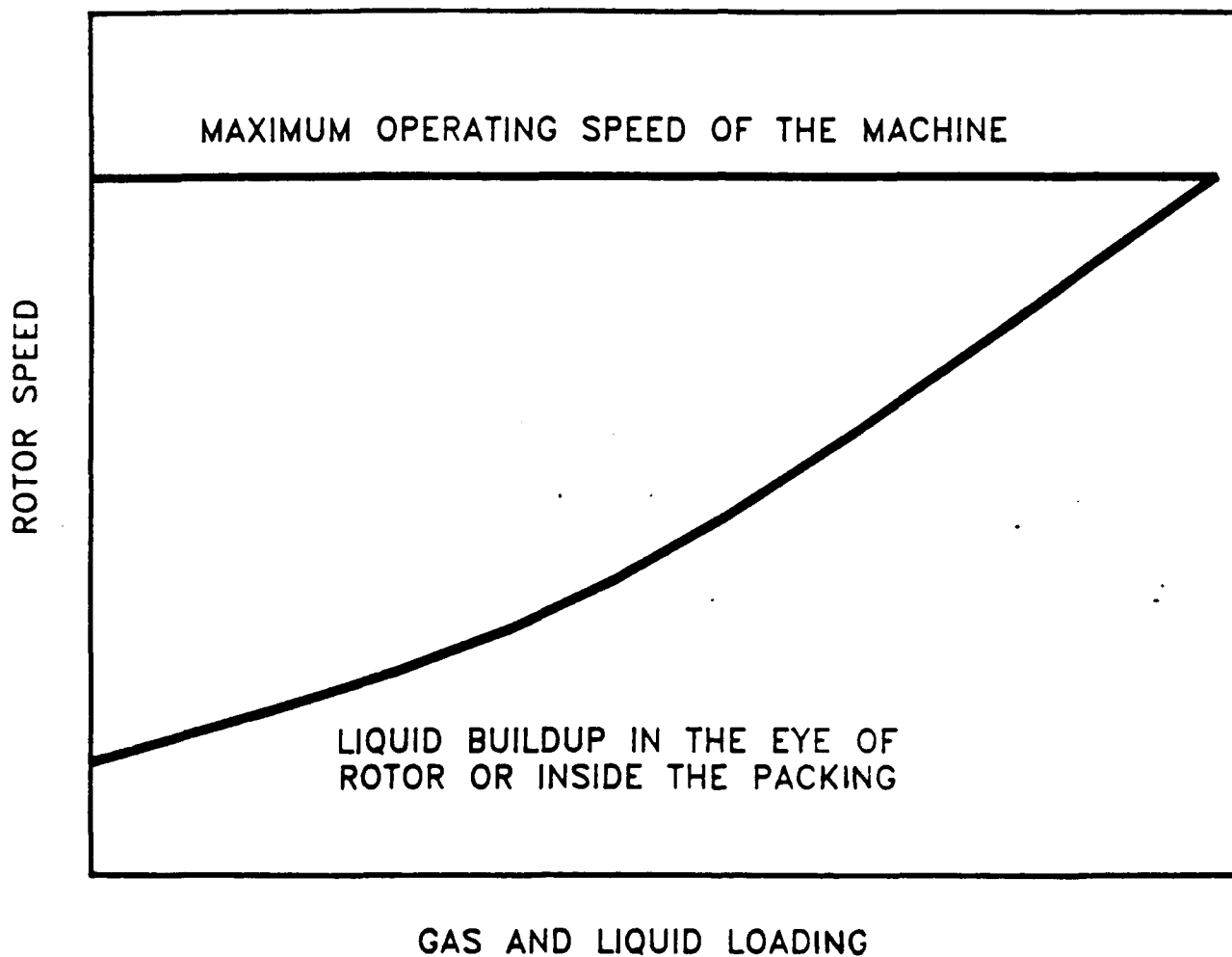


Figure 7. Theoretical Operating Envelope for the Centrifugal Vapor-Liquid Contactor.

#### a. Hydraulic Capacity Correlation

The limit of operability (onset of flooding) in conventional packed columns may be defined as a region of operating conditions where countercurrent flow of the two phases is disturbed and pressure drop across the column begins to oscillate. Although not totally applicable to the centrifugal vapor-liquid contactor, this definition can be useful in characterizing hydraulic performance. Unlike conventional packed towers in which the limit of operability (flooding) is achieved by increasing gas and liquid flows, flooding in a centrifugal vapor-liquid contactor can be initiated at constant fluid flows by decreasing the rotational speed of the packing torus. This approach was utilized in developing a hydraulic capacity correlation. The Sherwood flooding correlation for conventional packed towers has been recommended by several authors (References 23 and 27) for designing a centrifugal vapor-liquid contactor. Thus, it will be beneficial to compare data from this study with the Sherwood flooding correlation.

#### b. Pressure Drop Correlation

The pressure drop across the rotating packing torus of a centrifugal vapor-liquid contactor is difficult to model theoretically. Thus, a semitheoretical approach based on experimental observation was used. The pressure drop across the packing can be divided into two terms. The first term accounts for the pressure drop due to rotation of the packing, and the second term accounts for pressure drop resulting from the flow of fluids through a porous media.

The rotational pressure drop term can be modeled theoretically. In a packing torus rotating at a constant speed, the centrifugal force, acting on a fluid element of volume  $dV$  and density  $\rho$  at a radius  $r$  from the axis of rotation, has a value of  $\rho r \omega^2 dV$  (Reference 27), where  $\omega$  is the rotational speed. The resulting pressure can be calculated by dividing the centrifugal force by the area perpendicular to the radius on which it acts. In differential form, the pressure drop across the packing torus can be written as:

$$dP = \rho \omega^2 r dr \quad . \quad (50)$$

Integrating this equation between the inner ( $r_1$ ) and the outer ( $r_2$ ) radii gives:

$$P_{rot} = \frac{\rho_{air} \omega^2}{2} (r_2^2 - r_1^2) \quad . \quad (51)$$

Since it is difficult to measure pressure drop very close to the inner and outer radii, a constant,  $A$ , can be introduced to account for end effects, and Equation (51) becomes:

$$P_{rot} = A \frac{\rho_{air} \omega^2}{2} (r_2^2 - r_1^2) \quad (52)$$

The pressure drop caused by flow of fluid through a porous media is conventionally modeled as consisting of a viscous term and an inertial term (Reference 29). This can be expressed as:

$$\frac{\Delta P_{flow}}{l_p} = \alpha \mu V_F + \beta \rho V_F^2 \quad (53)$$

Several complications arise in trying to apply Equation (53) to the centrifugal vapor-liquid contactor. First, Equation (53) assumes that the superficial velocity remains constant through the entire depth of the porous medium. This is not the case for the packing torus because the cross sectional area changes with the radius. Second, Equation (53) assumes pressure drop varies linearly with depth of packing, and this may not be true for the packing torus. These assumptions can be addressed by use of an average superficial velocity through the packing torus. Then, if the difference between the inner and outer radii is small, linear dependence of pressure drop with packing torus may be a reasonable assumption.

### 3. Power Consumption

Power consumption for a centrifugal vapor-liquid contactor can be modeled using two distinct terms. The first term can be used to account for all the frictional losses, and the second term to account for the power required to accelerate the liquid entering the packing torus to the rotational speed at the outer radius. The frictional losses are highly dependent upon the design of the machine and cannot be predicted without advanced knowledge of the design (i.e., type of bearings, direct or pulley drive, etc.). The power required to accelerate the liquid, on the other hand, can be described by a theoretical model (Reference 29). The overall power consumption can thus be written as:

$$P_c = A + B \rho_L r_2^2 \omega^2 Q \quad (54)$$

where A and B are regression coefficients.

### C. EMISSION CONTROL DEVICES

The modeling of performance of the catalytic incineration and carbon adsorption is done on a very simple basis. The incinerator performance is expressed as percentage efficiency, which is defined for a particular chemical specie as

$$\text{Efficiency} = 100(y_{in} - y_{out})/y_{in} \quad (55)$$

The modeling of the adsorber is based on the change in effluent mole fraction vs time as the bed becomes loaded with adsorbed material. A trace of the quantity  $y_{out}/y_{in}$  for a particular chemical specie vs time is known as a breakthrough curve.

## SECTION III

### EXPERIMENTAL SYSTEM

A schematic of the air stripping and emissions control system used in the field tests is shown in Figure 8 (see page xxx for symbols legend). The contaminated groundwater from the wells was passed through a 50  $\mu\text{m}$  filter (Cole-Parmer) and routed to a 6.57  $\text{m}^3$  surge tank. The surge tank contained 38 mm polypropylene balls, which covered the entire water surface, to minimize the loss of VOCs. The water could be pumped from the bottom of the surge tank either to the packed column or the rotary air stripper. If desired, the tank could be bypassed and the groundwater pumped directly from the wells to the strippers. However, to eliminate the possibility of pumping "free product" jet fuel from a groundwater well directly into a stripper, the surge tank was always utilized. If any jet fuel was present, it would be removed in the overflow from the surge tank.

The VOC-depleted water from the strippers was discharged to an existing aeration basin. The air to both strippers was supplied by a blower with a capacity of 0.33  $\text{m}^3/\text{second}$ . The air stream exiting either the packed column or the rotary air stripper was passed through a knock-out drum equipped with two demister elements to remove excessive quantities of mist that might be carried over from the two strippers. The two demister elements were necessary to provide effective mist elimination over the wide range of air flows. The major portion of the air from the knockout drum was discharged to the atmosphere, while a small slip stream was routed either to the activated carbon bed or the catalytic destruction unit. If required, the carbon bed and the catalytic destruction unit could be operated simultaneously. Activated carbon was also replaced by molecular-sieve material for other tests. The air streams coming from the carbon bed and the catalytic unit were discharged to the atmosphere. The packed column air stripper, the centrifugal stripper, the activated carbon bed, and the catalytic destruction unit are described in more detail below.

#### A. CONVENTIONAL COUNTERCURRENT PACKED COLUMN AIR STRIPPER

A schematic of the packed column is shown in Figure 9. The packed portion of the column was constructed from 12-inch Schedule 5 stainless-steel pipe in 1.52-meter sections to facilitate transportation and handling in the field. A 0.76-meter diameter x 1.57-meter long stainless-steel tank (fabricated from thin sheet metal), shown in Figures 10 and 11, served as the wet well for the column. Air from the blower was introduced into the tank through the 4-inch inlet pipe, as shown in Figure 11. A baffle prevented the air from impinging directly on the surface of the water in the tank. The velocity of the air decreases significantly as it passes from the inlet pipe into the upper half

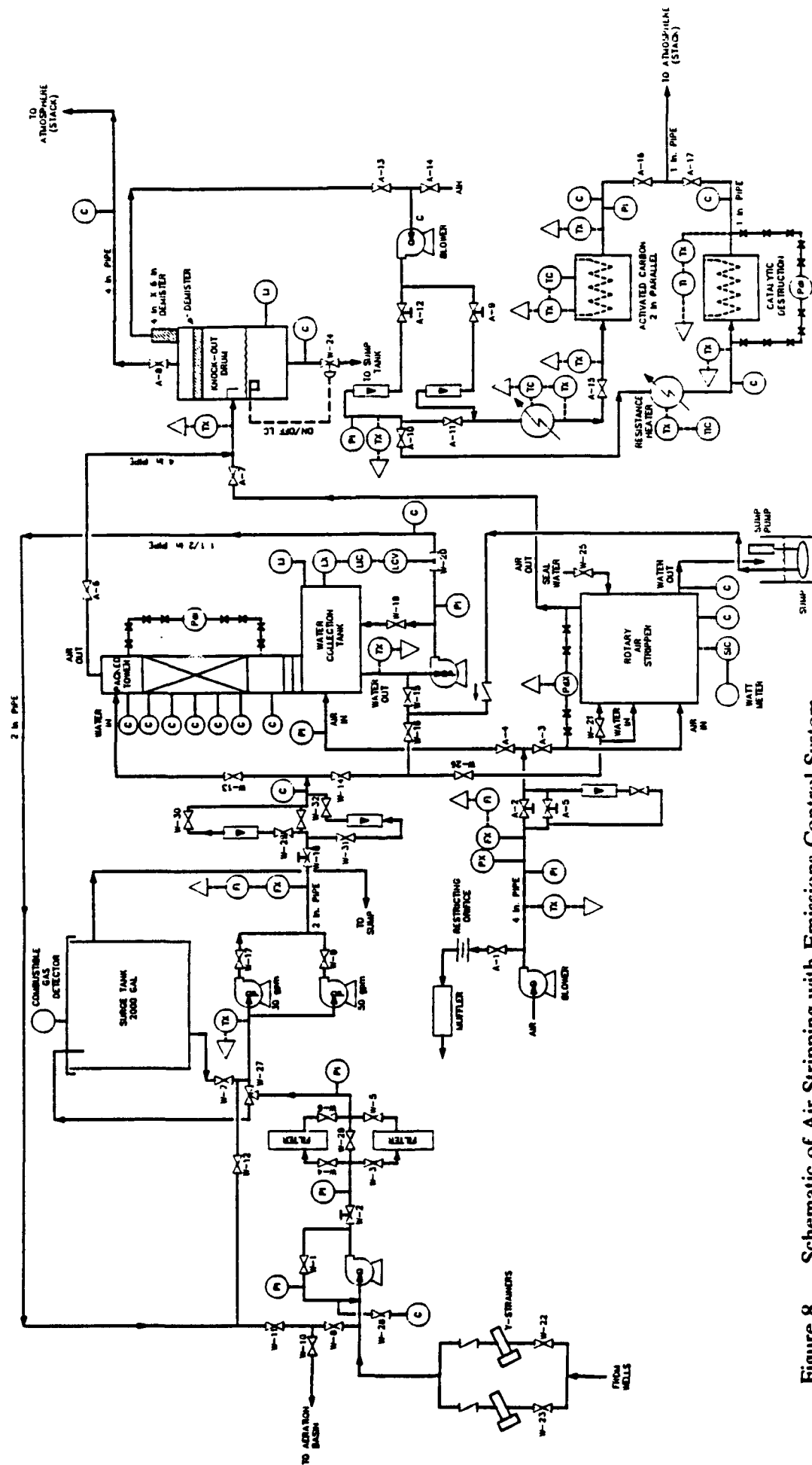


Figure 8. Schematic of Air Stripping with Emissions Control System.



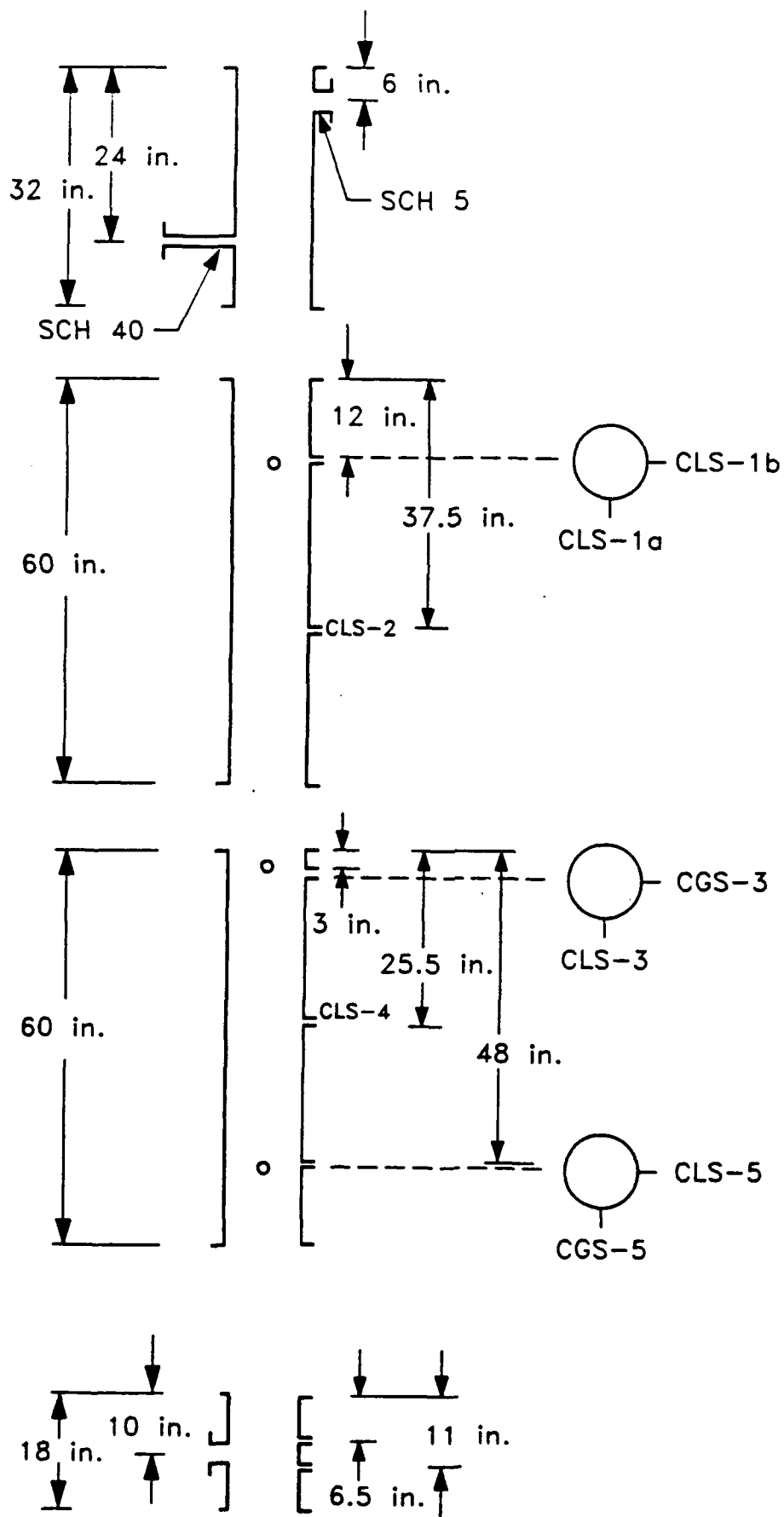


Figure 9. Schematic of Packed Tower.



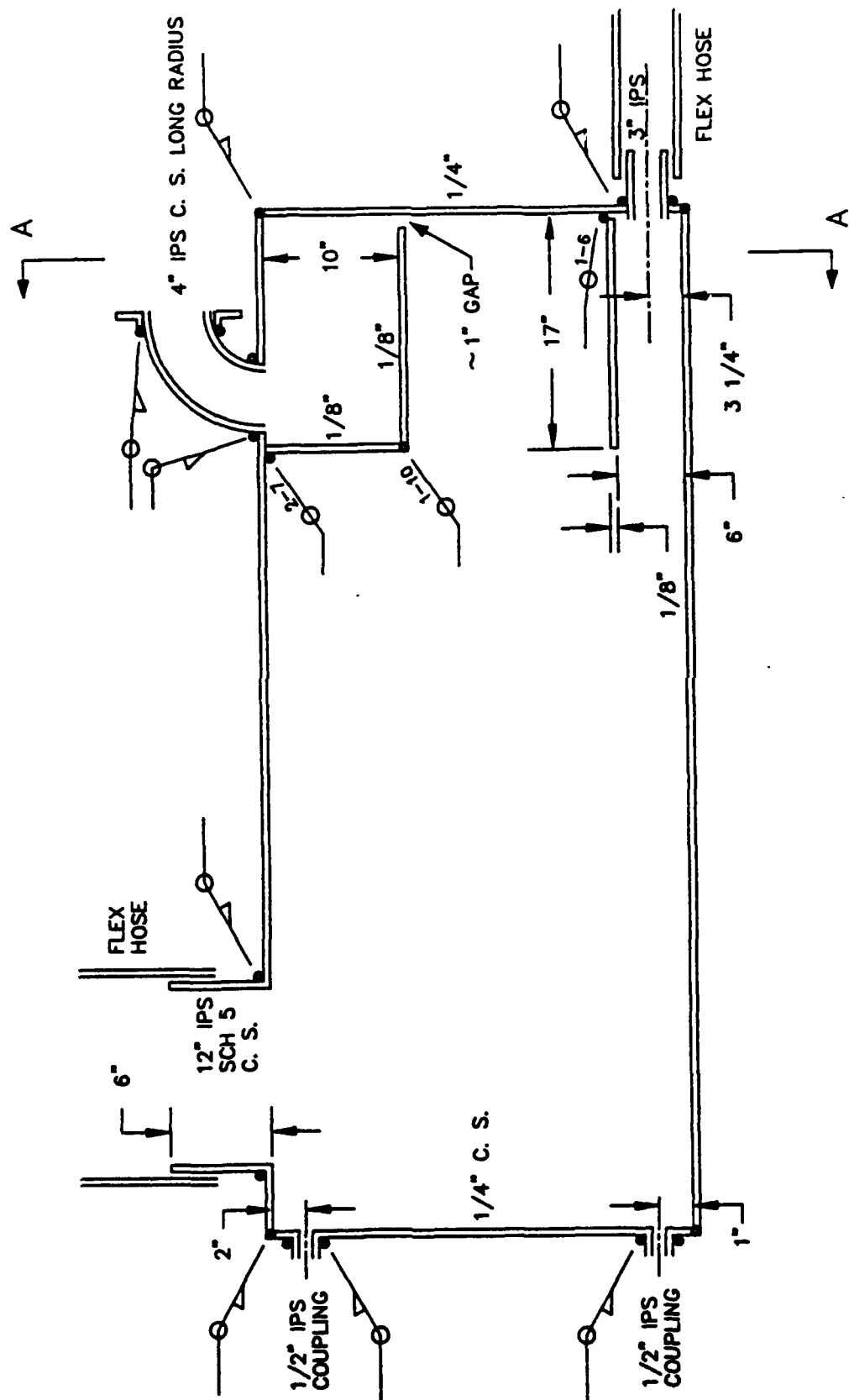


Figure 11. Detail of the Wet Well.

(above the water level) of the wet well. This type of arrangement was designed to provide uniform air distribution at the inlet to the stripper column. Above the tank and below the packing support, sight glasses were combined with sampling probes to permit visual inspection and measurement of the mass flow distribution of the water draining from the column. Three gas sample taps and five liquid sample taps were provided in the packed section of the column. The sampling taps were rotated about the circumference of the tower to minimize flow disruptions, such as could occur if all the samples taps were located on one side of the column.

Four different types of packing were used in the stripping tests with the packed column; 1.6 mm stainless-steel Flexirings®, Koch/Sulzer (Koch Engineering Co., Inc., Wichita, Kansas) structured packing, Koch/Sulzer type BX plastic packing, Koch Flexiramic® Packing, and Delta SH (Delta Cooling Towers, Inc., Fairfield, NJ) structured packing. A Koch Model 101 flange-ring mounted support plate was used for the Flexiring® packing support. The Koch structured packings were supported by a special support plate supplied by Koch. The Delta SH packing rested on the flange ring.

A Koch 301B flange-mount distributor was installed above the packed section of the column. This distributor was used with the Flexiring® packing and the Koch packings. The distributor was designed to accommodate the wide range of liquid flow rates to be encountered in the field tests. The top portion of the column above the distributor was made from 16-gauge 304 stainless-steel sheet rolled and welded to produce a 0.30-meter inner diameter. Water was introduced onto the distributor using a feed pipe, shown in Figure 12, constructed to Koch's specifications (introduction onto the distributor at less than or equal to 1.53 meters/second). By coupling this feed pipe with the Koch wide flow range distributor, operation over the projected flow rate range was possible. In tests with the Delta SH packing, the distributor and feed pipe were replaced with a hollow-cone spray nozzle supplied by Delta Cooling Towers, Inc. The air exit pipe was located 0.15 meters below the top of the column. A plate of 0.13 mm Plexiglas was installed on the top of the column to allow inspection of the distributor.

## **B. CENTRIFUGAL AIR STRIPPER**

In the centrifugal stripper, centrifugal instead of gravitational, force is used to provide the driving force for liquid flow through the packing. A schematic of the centrifugal stripper is shown in Figure 13. The rotating packing was mounted on a vertical shaft so that the packing was oriented in the horizontal position. Two packings were evaluated in these tests. The first packing was made from thin sheets of porous metal (Sumitomo Electric Industries, Ltd., Japan) which were wound to

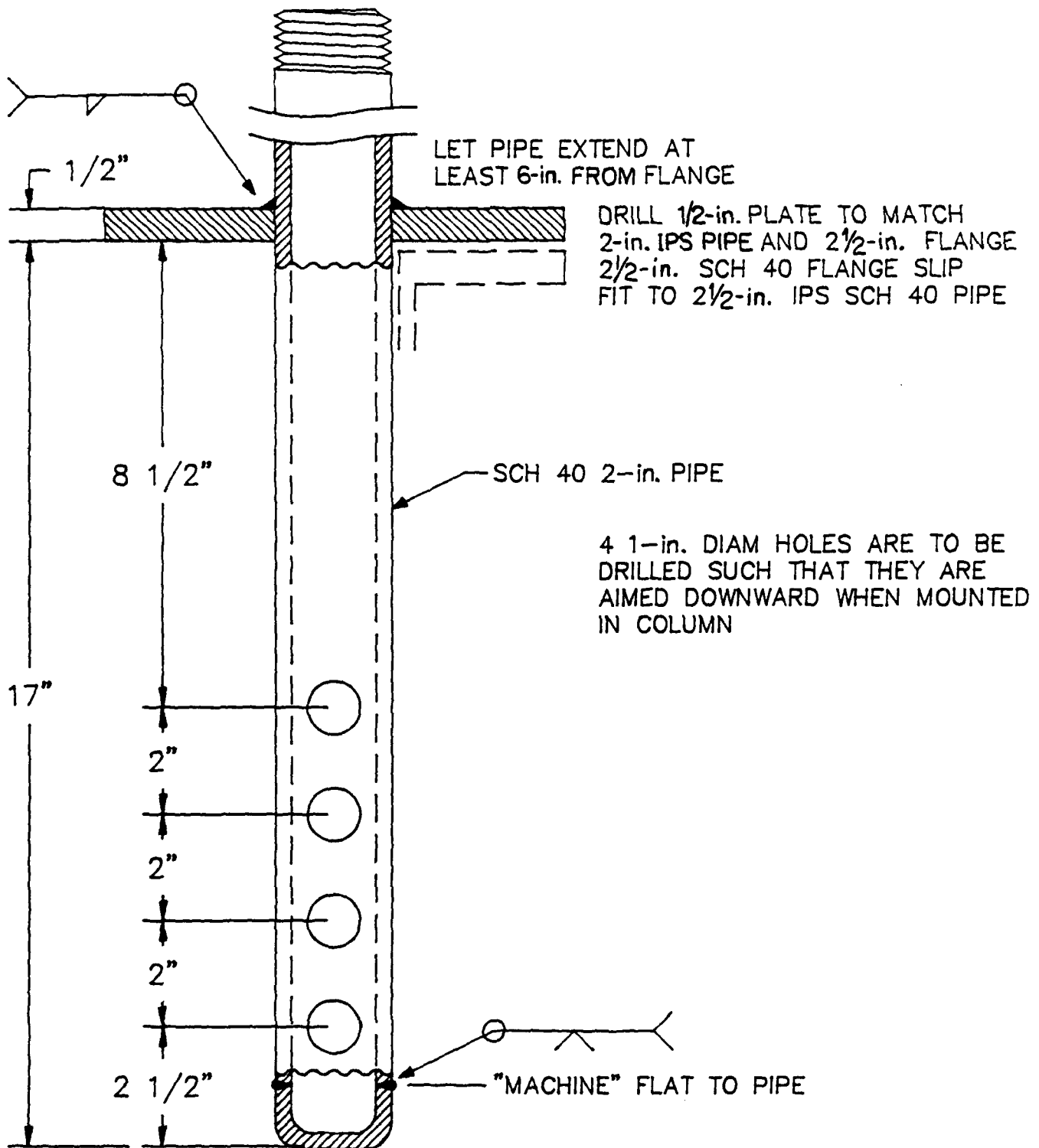


Figure 12. Feed Pipe Details.

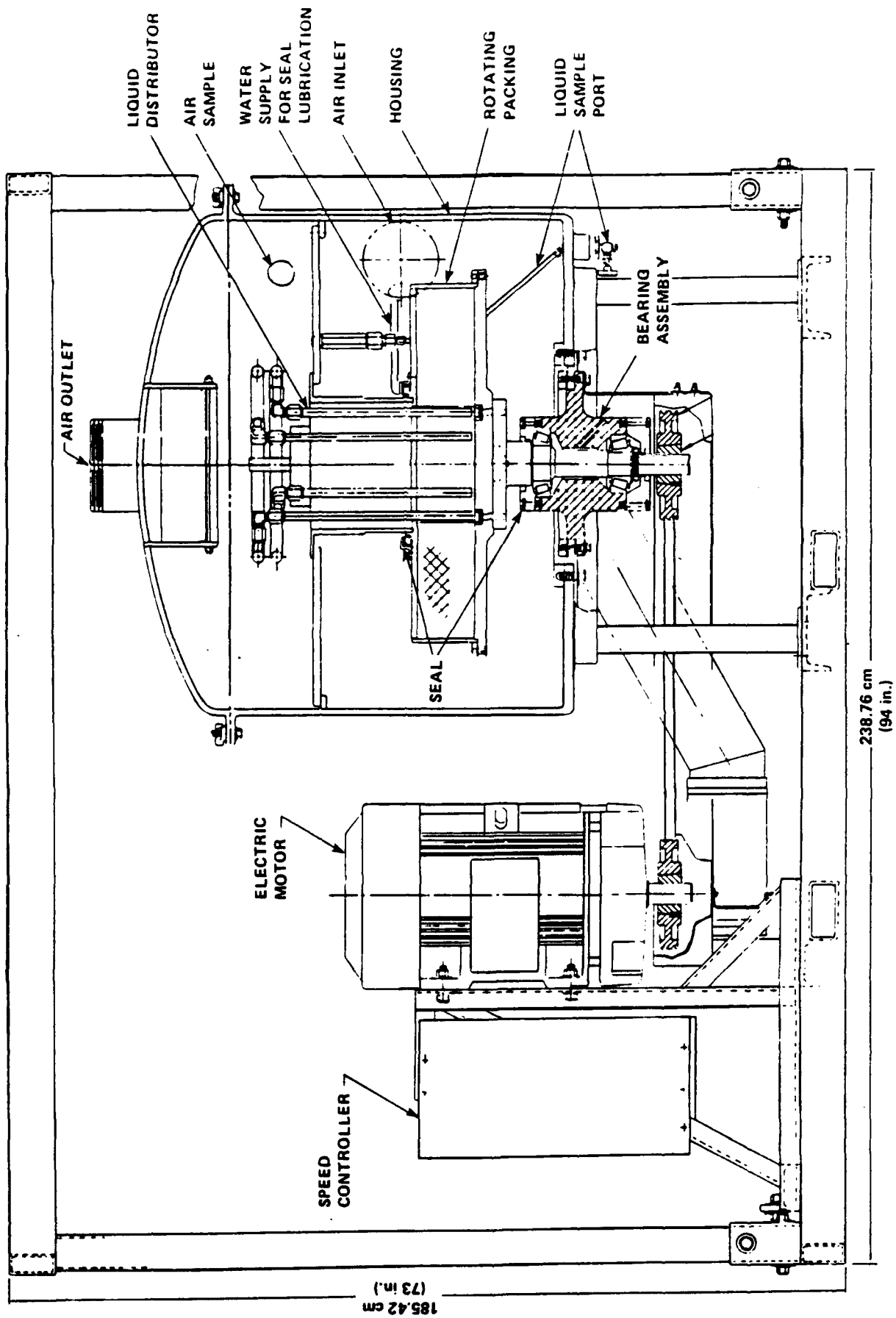


Figure 13. Rotary Air Stripper Skid Schematic.

give the proper packing depth. The packing material had a specific surface area of  $2500 \text{ m}^2/\text{m}^3$  and voidage of 0.95. The second packing was made from wire gauge and had a specific surface area of  $2067 \text{ m}^2/\text{m}^3$  and voidage of 0.934.

Water was introduced into the center of the rotating packing via a liquid distributor, which was made in two sections. Each section consisted of three 0.19 mm aluminum tubes spaced  $120^\circ$  apart connected to a common circular supply header. This split arrangement permitted operation over a wide range of liquid flow rates while maintaining adequate discharge velocity by simply closing off one section. The liquid from each tube exited through a series of 23.6 mm diameter holes. After the water exited from the rotating packing, it impacted the inside of the housing and flowed by gravity to a tank where it was pumped to the aeration basin.

Air was introduced into the housing through a 0.15-meter diameter opening tangential to the rotating packing. The air flowed inward because of the pressure driving force and contacted the water in a countercurrent mode. The unit was equipped with a demister element for the exiting air stream; however, this was not used in any of the experiments since entrainment of water was found to be negligible. This observation is different from that of Dietrich et al. (Reference 22).

The rotating packing was driven by a 220-volt, three-phase 20 hp motor. The speed of the motor was controlled by a variable frequency inverter.

It would be extremely difficult to withdraw samples from the inside of the rotating packing in order to determine mass transfer coefficients as a function of packing depth. To overcome this problem, three rotors with different outer radii were used for mass transfer studies. The outer diameters of the three rotors were 18, 24, and 30 inches, which produced packing depths of 4, 7, and 10 inches, respectively.

As shown in Figure 14, a sample tube was installed inside the housing next to the outer diameter of the packing. The radial location of the sample tube was changed when the rotors were changed. The purpose of this sampling system was to obtain a sample representative of the groundwater immediately exiting the rotor packing. Also, a measure of the removal of VOCs that occurred in the housing after the water exited the rotor was obtained from the concentration difference between a sample taken from the sampling tube and the water exit stream from the centrifugal stripper housing.

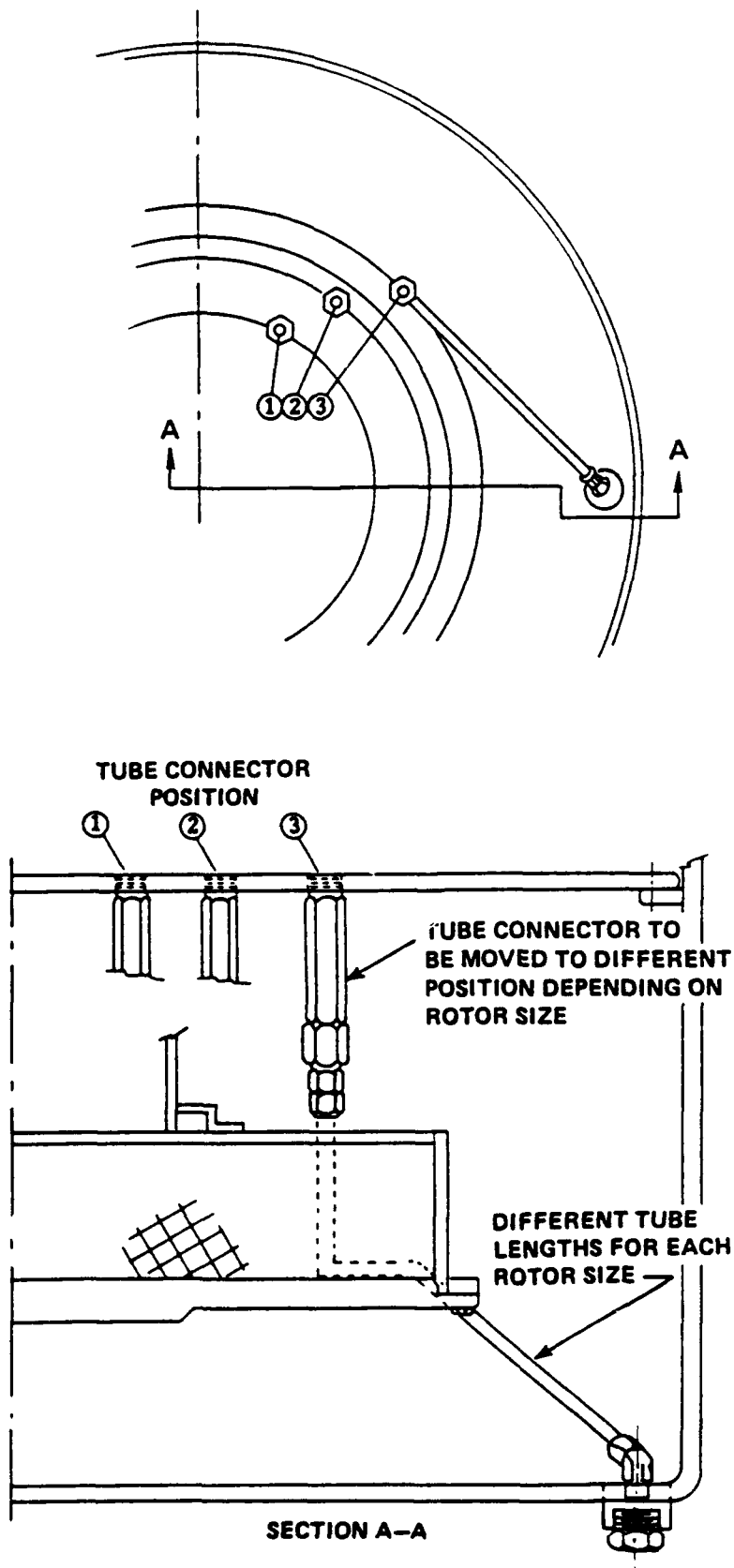


Figure 14. Sampling System for the Rotary Air Stripper.



The centrifugal stripper was designed for 0.0032 m<sup>3</sup>/second of water and 0.24 m<sup>3</sup>/second of air. At these flow rates, it was estimated that a rotor with inside diameter of 0.25 meters and axial length of 0.127 meters would flood at rotational speed of ~550 rpm. This assumed that the Sherwood flooding correlation, used to size the conventional packed air strippers, applied to the centrifugal stripper.

### C. CARBON ADSORPTION

Schematics of the carbon adsorption bed and its ancillary equipment are shown in Figure 15. The carbon adsorption bed was designed for a 2-day breakthrough of pentane at air feed conditions of 0.0047 m<sup>3</sup>/second and 0 percent relative humidity. The housing of the bed, made from thin-wall stainless-steel, was 0.20 meters in diameter x 0.51 meters long. The temperature of the carbon bed was regulated by resistance heaters on the outside of the bed housing. The adsorber was fed from the top by a 25.4 mm carbon steel pipe which was also heat-traced. A baffle was provided at the inlet to the bed to help disperse the air flow. Thermocouples were located on the outside of the housing and in the carbon bed itself.

Two carbon beds, which could be used alternately, were provided with the system. The flow could be changed from one bed to the other by closing and opening valves. The exit gas stream from each bed was discharged to the atmosphere.

In some tests, activated carbon was replaced by molecular sieves. The sieves tested, UOP 9102, UOP 13837-53, and UOP AIR-SP-S-115, were from the UOP Company.

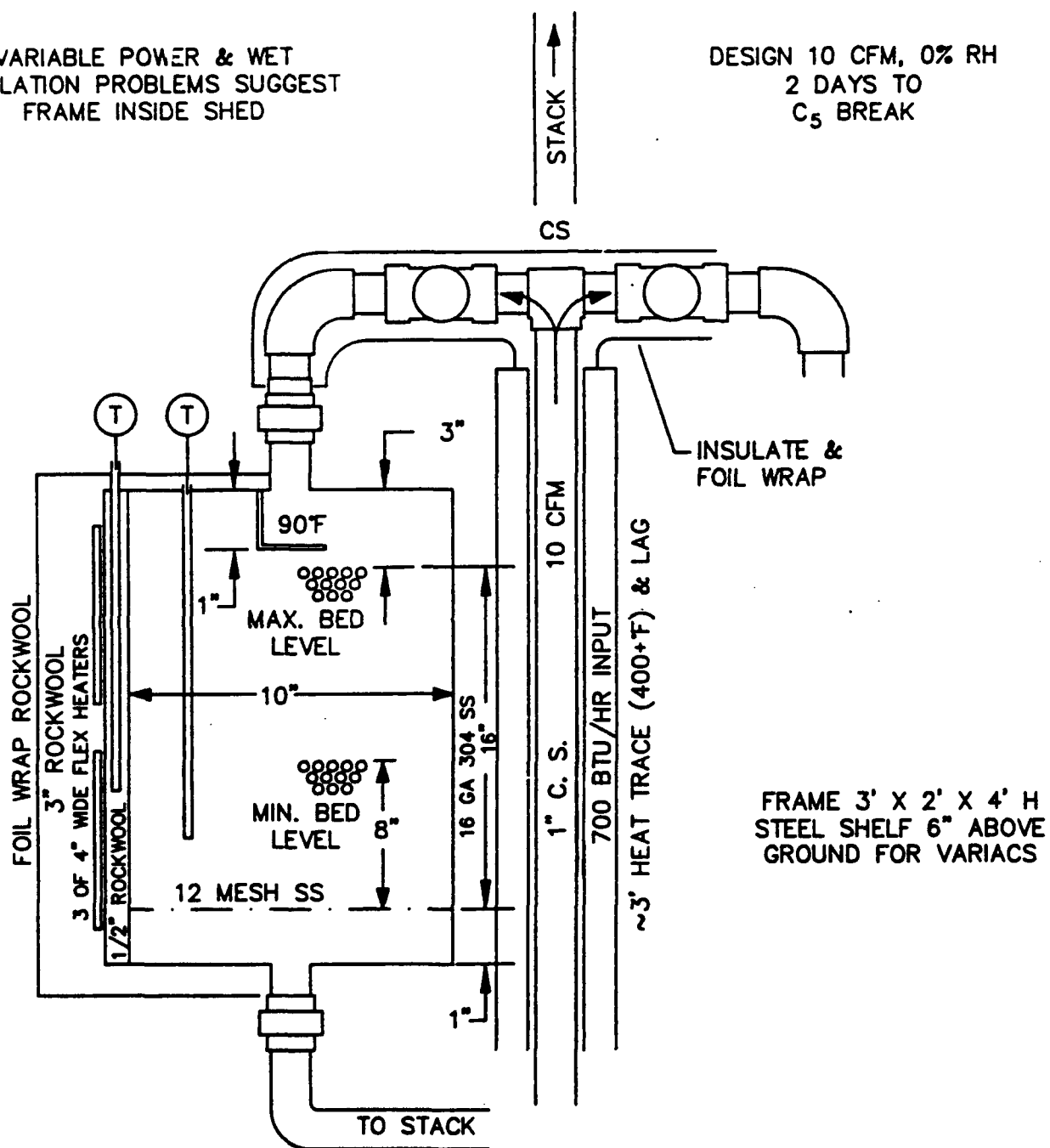
### D. CATALYTIC DESTRUCTION UNIT

A schematic of the catalytic destruction system, which was leased from the Engelhard Company, is shown in Figure 16. The catalytic reactor system, which was skid-mounted, consisted of a blower, electric preheater, catalytic reactor, and process monitoring instruments. A blower (Rotron Simplex Spiral Blower Model No. SL2P2) was used to draw 0 to 0.012 m<sup>3</sup>/second of air from the exit stream of the air stripper. The air then flowed through a flowmeter (Brooks Rotometer) and into the preheater (General Electric Calrod Circulation heater). The preheater was a 4.5 kW heater with type 321 stainless-steel elements. Watt density was 11 watts/in.<sup>2</sup>. The heater was controlled by a Honeywell Dialatrol temperature controller TIC-1 (inlet thermocouple).

The catalytic reactor contained an Engelhard proprietary catalyst. The catalyst was a precious metal formula on a honeycomb ceramic substrate. Two types of catalyst were tested, one with an initiation temperature of 316°C, and the other with an initiation temperature of 204°C. The catalyst bed consisted of three elements in series, each 25.4 mm in diameter x 76.2 mm long. Thus, it was

VARIABLE POWER & WET  
INSULATION PROBLEMS SUGGEST  
FRAME INSIDE SHED

DESIGN 10 CFM, 0% RH  
2 DAYS TO  
C<sub>5</sub> BREAK



2 OF 10" D X 20" H  
22 TO 16 GA 304 SS POTS

Figure 15. Carbon Bed Design.

# LEGEND

FI FLOW INDICATOR  
 TIP OVERTEMP. = SHUT OFF  
 TIC TEMP. = CONTROLLER  
 TI TEMP. = INDICATOR  
 DPI DIFFERENTIAL PRESS INDICATOR  
 FV CONTROL VALVE

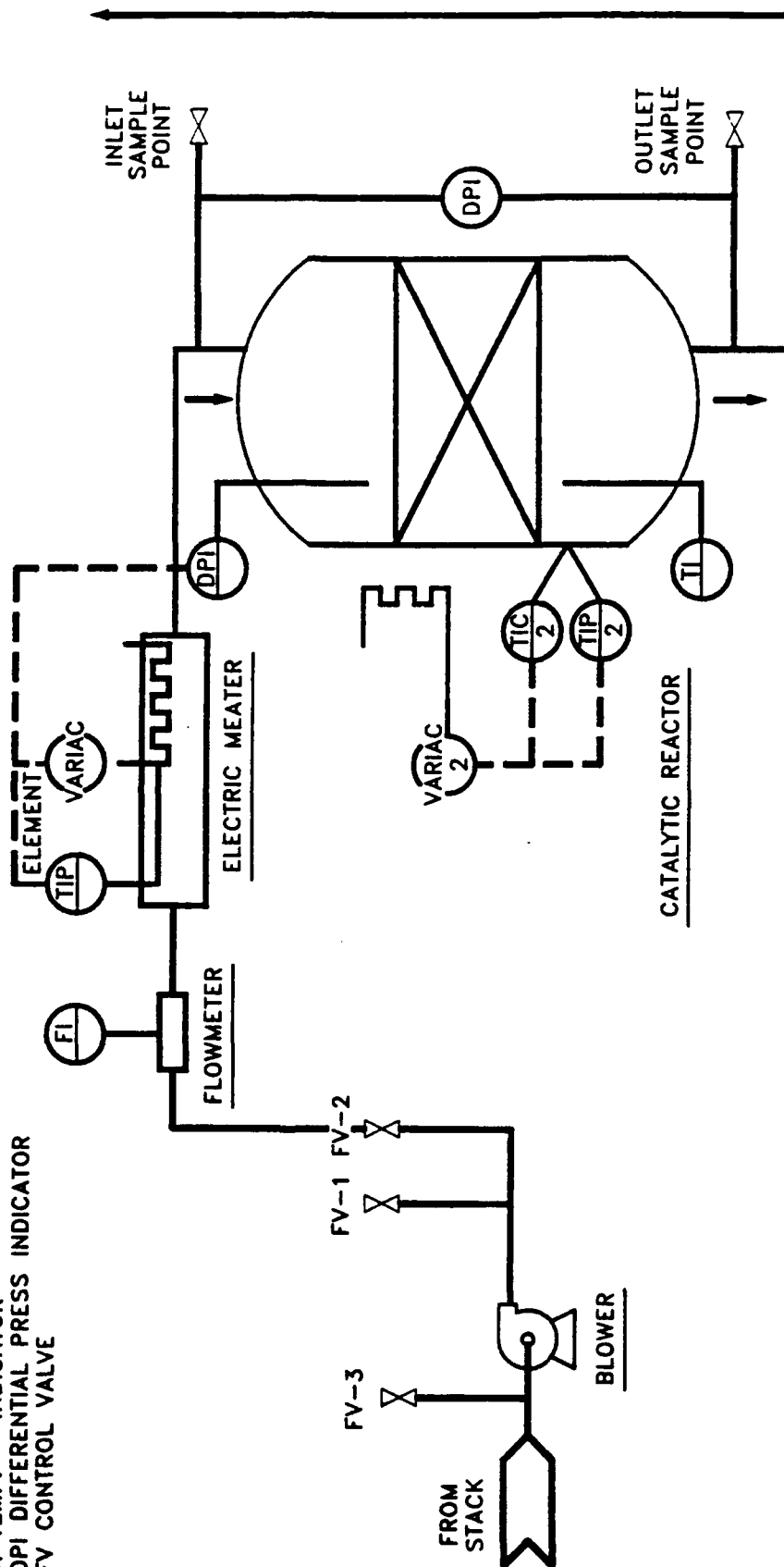


Figure 16. Flow Schematic of Catalytic Reactor System.

possible to vary the volume of the catalyst by installing 1, 2, or 3 elements into the reactor. This would permit the study of the effect of space velocity at a constant Reynolds number. The heat loss from the catalyst bed was minimized by using strip heater elements on the outside of the shell. The reactor was automatically shut off if the heater bed temperature exceeded a preset value. The exhaust gas from the reactor was discharged to the atmosphere. Sample points were provided at the inlet and the outlet of the reactor to allow measurement of conversion across both the preheater and the catalytic bed.

## **E. IMPORTANT ANCILLARY EQUIPMENT**

### **1. Analytical Equipment**

The liquid and gas samples were analyzed using a Tracor 540 gas chromatograph (GC) (Tracor Instruments Austin, Inc., Austin, Texas) equipped with a Megabore column (3 micron film thickness (DB-624), 30 meters long, 0.544 mm I.D., Cat. No. 1251334, J&W Scientific, Folsom, California), flame ionization detector, and a Spectra-Physics SP4270 Integrator (Spectra-Physics, San Jose, California). The hydrogen fuel for the GC was supplied using an Elhygen Mark V hydrogen generator (LDC/Milton Roy Chromatography Systems). For concentration of the volatile hydrocarbons in the liquid samples, the analytical system also contained a Tekmar Liquid Sample Concentrator (LSC 2000) purge and trap apparatus and a Model ALS automatic laboratory sampler (Tekmar Company, Cincinnati, Ohio). The ALS was a 10 station sampler equipped with Supelco needle sparge samplers (Cat. no. 2-2724, Supelco, Inc., Bellefonte, Pennsylvania). The LSC apparatus contained a Tenax trap for the capture and concentration of the VOCs. After capture of the compounds on the Tenax trap from either gas or liquid samples, they were desorbed and injected into the GC for analysis.

### **2. Blower and Pumps**

The air blower used in the field tests had a 0.61 meter aluminum wheel assembly and housing and was manufactured by New York Blower (size 2406A10). The blower was powered by a Siemens-Allis 10 hp 3500 rpm motor (model 127). This package arrangement was capable of delivering 0.33 m<sup>3</sup>/second of air at 21°C and a 1.14-meter water static pressure. Three pumps for movement of the water being treated were powered by 1-1/2 hp 3500 rpm Baldor motors (model VL3513). The centrifugal pump heads were manufactured by Eastern (Model 88).

### **3. Instrumentation**

The primary air flow rate to the air stripper was measured by calibrated orifice meters. The water flow rate to the air stripper was measured by a Signet paddlewheel sensor with a range of zero to 0.0050 m<sup>3</sup>/second. Pressure sensing was by various Bourdon gauges and electronic differential pressure sensors. Temperature measurement was by type K thermocouples.

### **4. Data Acquisition and Programs**

Data acquisition and control of some process parameters were accomplished by using an IBM-AT compatible personal computer with LabTech Notebook as the data acquisition and control software. The personal computer was linked through Metrabyte Corp. interface cards to transducers that measured flow rates, temperatures, and pressures, etc., at various points in the system. The data from these transducers was collected at programmed intervals and stored in a Lotus 1-2-3 spreadsheet format allowing for rapid data analysis at the end of a run. Individual runs could be analyzed and compared with previous runs very quickly, which allowed for repetition of a given run if process parameters were not adequately controlled.

## SECTION IV

### EXPERIMENTAL AND ANALYTICAL PROCEDURES

#### A. EXPERIMENTAL DESIGN

A central composite design was chosen for the experiments to reduce the number of runs for the mass-transfer tests\*. A description of this design, presented by Anderson and McLeon (Reference 30), is given below.

The composite design (References 31, 32, and 33) has three parts: a basic two-level factorial or fractional factorial, an extra point at the center of the entire design, and  $2k$  (where  $k$  = number of factors) extra points, one at either extreme of each factor and at the center of all other factors. Hence, in a composite design with a complete factorial experiment in it, there would be  $2^k + 2k + 1$  treatment combinations. Correspondingly, if there was a fractional factorial instead of a complete factorial experiment in the design, the  $2^k$  would be reduced as required. The particular type of composite design depends on the location of the extreme points. If the extreme points are located at the same standardized distance from the center point as the factorial points, the design is called a rotatable composite design (sometimes the word "central" is included in the title of these designs to indicate that there is a center point). If the extremes are located at a distance that makes the squared terms in the model orthogonal to each other, the design is called an orthogonal composite design. Any other location of the extreme points may be used, but the analysis is just a nonorthogonal regression analysis.

The advantage of a composite design over the fractional or complete three-level factorial is in the reduction of the number of treatment combinations required to estimate the squared terms in a second-order model. This idea may be summarized in the following tabulation:

---

\*Hebble, T. L., Personal Communication, Oak Ridge National Laboratory.

NUMBER OF FACTORS $k$	NUMBER OF TREATMENT COMBINATIONS	
	THREE-LEVEL FACTORIAL, $3^k$	COMPOSITE, $2^k + 2k + 1$
2	9	9
3	27	15
4	81	25
5	243	43
5	(1/3 fractional) 81	(1/2 fractional) 27
6	729	77
6	(1/3 fractional) 243	(1/2 fractional) 45

As the number of factors increase in an experiment, the savings in number of runs using the composite design instead of the three-factor factorial increases rapidly.

Two disadvantages in using the composite design instead of the three-leveled factorial are (1) estimating effects with unequal variances and (2) having fewer degrees of freedom for error. The model for a composite design is:

$$\gamma = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \beta_{12} X_1 X_2 + \dots + \beta_{(k-1)k} X_{k-1} X_k + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \dots + \beta_{kk} X_k^2 + \epsilon$$

Consider  $k = 3$ . The composite model is:

$$\gamma = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \epsilon$$

where the error has five degrees of freedom, and the corresponding model for the three-leveled factorial is:

$$\begin{aligned}
\gamma = & \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \\
& + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 \\
& + \beta_{112} X_1^2 X_2 + \beta_{122} X_1 X_2^2 + \beta_{113} X_1^2 X_3 + \beta_{133} X_1 X_3^2 + \beta_{233} X_2 X_3^2 \\
& + \beta_{223} X_2^2 X_3 + \beta_{1122} X_1^2 X_2^2 + \beta_{1133} X_1^2 X_3^2 \\
& + \beta_{2233} X_2^2 X_3^2 + \beta_{123} X_1 X_2 X_3 + \beta_{1123} X_1^2 X_2 X_3 \\
& + \beta_{1123} X_1 X_2^2 X_3 + \beta_{1233} X_1 X_2 X_3^2 + \beta_{11233} X_1^2 X_2^2 X_3 \\
& + \beta_{11233} X_1^2 X_2 X_3^2 + \beta_{12333} X_1 X_2^2 X_3^2 + \beta_{112333} X_1^2 X_2^2 X_3^2 \quad .
\end{aligned}$$

In a second-order model, the terms from  $\beta_{112} X_1^2 X_2$  through  $\beta_{11233} X_1^2 X_2^2 X_3^2$  are assumed as zero and could be put into the error estimates. The factorial model would then allow 17 degrees of freedom error. In general, for optimum designs, the five degrees of freedom in the composite design for the error estimate are adequate and the composite design is preferred over the three-level factorial.

### 1. Conventional Packed Tower

The purpose of the tests with the conventional packed column was to generate data on the hydraulic and mass transfer characteristics of different types of packing which can be used for design of full-scale towers and for comparison with the results from the centrifugal stripper tests. The four types of packing which were tested were 16 mm stainless-steel Flexirings®, Koch/Sulzer packing, Koch Flexiramic® packing, and Delta SH packing. The Flexirings® represented a typical random packing (although 25 to 26 mm Flexirings® would be used in a large-scale operation, 16 mm rings were used in these tests to minimize wall effects in the 0.3 meter diameter column). The Koch/Sulzer packing was a high efficiency structured packing, the use of which should significantly reduce the height of a stripping column required for a certain VOC removal efficiency. This structured packing may also be less susceptible than random-type packings to plugging by iron deposits. The Delta SH packing was also a structured packing which has very low pressure drop characteristics. In large-scale systems, low pressure drop is particularly desirable because of power costs. Furthermore, the Delta SH packing was thought to be useful for stripping of groundwaters containing high concentrations of iron.

A large amount of data exists for operation of conventional countercurrent columns at high gas-to-liquid ratios. The philosophy behind the tests described herein was to generate data at conditions which may be expected to be utilized when emissions control devices are required, i.e., lower gas-to-liquid ratios to minimize capital and operating costs. Thus, most of the mass transfer



tests were performed at stripping factors ranging from 1 to 4. Several points were taken at higher stripping factors to compare the performance of this column to other columns.

The hydraulic tests for the packed column were designed to obtain pressure drop as a function of liquid and gas rates over the "usable capacity" of the various packings. This capacity was not likely to exceed pressure drops of greater than 800 Pascals/meter of packing. The mass-transfer tests were designed to provide information on the overall  $H_{iOL}$  for several typical "jet fuel components" over the usable capacity of the various packings.

The test conditions and the data collection requirements for the hydraulic and the mass transfer tests are shown in Tables 2 and 3, respectively. The detailed experimental design for the mass transfer tests is shown in Table 4, which shows a random-order schedule for the runs. The center point of the experimental design was repeated every other run in order to determine if there were any significant changes with time.

## **2. Centrifugal Stripper**

The purpose of the centrifugal stripper tests was to determine the hydraulic and mass transfer performance characteristics of the unit and to generate data which could be used either to verify existing design correlations or to derive new ones. Since very little data were available in the literature on the performance of the centrifugal stripper, data were collected over a wide range of operating conditions. Particular attention was given to operation at air-to-water ratios, where removal efficiencies are relatively low, in order that the area of a transfer unit ( $A_{iOL}$ , as defined later) could be calculated with a reasonable degree of certainty. That is, the air-to-water ratios were limited by the ability to measure, with confidence, low VOC concentration levels in the water exiting the stripper.

The operating conditions and data collection requirements for the hydraulic and mass transfer tests are shown in Tables 5 and 6, respectively. As in the case of the packed column mass transfer tests, a composite design for the experiments was chosen. The detailed experimental design is given in Table 7.

## **3. Activated Carbon Bed**

The primary purpose of the packed carbon bed experiments was to determine the adsorption behavior of a multicomponent hydrocarbon feed (at low concentrations in air) and to confirm the repressive effect of water vapor on the capacity of the activated carbon. The capacity of the carbon, as measured by time-to-breakthrough, was determined at several operating conditions.

TABLE 2. HYDRAULIC TEST CONDITIONS FOR THE PACKED TOWER

LIQUID FLOW RATE $\text{m}^3/\text{s}$	LOADING <sup>a</sup> $\text{kg}/\text{m}^2\text{-s}$
0.0	0
0.00041	5.22
0.00068	8.60
0.00131	16.71
0.00194	24.73
0.00221	28.11
CRITERIA FOR ACCEPTING A RUN	
VARIABLE	ACCEPTABLE VARIANCE
Liquid flow	0.001 $\text{m}^3/\text{s}$ for 15 min or $\pm 5\%$ of set point
Gas Flow	$\pm 5\%$ of set point for 15 min

<sup>a</sup>The flow rates were used for all four packings.

TABLE 3. MASS TRANSFER TEST CONDITIONS FOR THE PACKED TOWER

<b>PACKING MATERIALS</b>	
1.	16 mm stainless steel Flexirings®
2.	Structured packing (Koch/Sulzer)
3.	Delta SH packing
4.	Ceramic packing (Koch)
<b>LIQUID FLOW RATE (LOADING) LEVELS:</b>	
1.	0.00041 m <sup>3</sup> /s (5.22 kg/m <sup>2</sup> -s)
2.	0.00068 m <sup>3</sup> /s (8.56 kg/m <sup>2</sup> -s)
3.	0.00131 m <sup>3</sup> /s (16.71 kg/m <sup>2</sup> -s)
4.	0.00194 m <sup>3</sup> /s (24.73 kg/m <sup>2</sup> -s)
5.	0.00221 m <sup>3</sup> /s (28.11 kg/m <sup>2</sup> -s)
<b>STRIPPING FACTOR* (BASED ON M-XYLENE) LEVELS:</b>	
1.	1.0
2.	1.4
3.	2.5
4.	3.6
5.	4.0
Variables to be monitored: Air flow rate, liquid flow rate, inlet-outlet gas and liquid temperature, and pressure drop.	
Samples to be taken: Inlet and outlet gas and liquid samples and liquid samples from the packed section.	
<b>COMPOUNDS TO BE ANALYZED FOR:</b>	
1.	Benzene
2.	1,2,4-trimethylbenzene
3.	Methyl cyclohexane
4.	Pentane
5.	Toluene

TABLE 3. MASS TRANSFER TEST CONDITIONS FOR THE PACKED TOWER (CONCLUDED)

COMPOUNDS TO BE ANALYZED FOR (CONTINUED):	
6.	m-Xylene
7.	o-Xylene
8.	Naphthalene
CRITERIA FOR ACCEPTING A RUN:	
VARIABLE	ACCEPTABLE VARIANCE
Liquid flow	$\pm 5\%$ of set point
Gas flow	$\pm 5\%$ of set point for one hour
Temperature	$\pm 1^{\circ}\text{F}$
Pressure drop	$\pm 10\%$ of average value

\*Stripping factor is equal to  $mG/L$ , where  $m = y/x$ , and  $G$  and  $L$  are the gas and liquid rates, respectively, in mol/s.

TABLE 4. CENTRAL COMPOSITE DESIGN FOR PACKED TOWER

RUN NUMBER	LIQUID RATE $\text{m}^3/\text{s}$	STRIPPING <sup>a</sup> factor
1 <sup>b</sup>	0.0013	2.5
2	0.0019	1.4
3 <sup>b</sup>	0.0013	2.5
4	0.0022	2.5
5 <sup>b</sup>	0.0013	2.5
6	0.0004	2.5
7 <sup>b</sup>	0.0013	2.5
8	0.0013	1.0
9 <sup>b</sup>	0.0013	2.5
10	0.00068	3.6
11 <sup>b</sup>	0.0013	2.5
12	0.0013	4.0
13 <sup>b</sup>	0.0013	2.5
14	0.0019	3.6
15 <sup>b</sup>	0.0013	2.5
16	0.00068	1.4
17 <sup>b</sup>	0.0013	2.5

<sup>a</sup>Stripping factor is equal to  $mG/L$ , where  $m = y/x$ , and  $G$  and  $L$  are the gas and liquid rates, respectively, in mol/s.

<sup>b</sup>Center point of experimental design repeated every other run in order to determine if there were significant changes with time.

TABLE 5. HYDRAULIC TEST CONDITIONS FOR THE CENTRIFUGAL STRIPPER

<b>ROTOR</b>	
1. Rotor 1 - 18-in.-diam	
2. Rotor 2 - 24-in.-diam	
3. Rotor 3 - 30-in.-diam	
<b>LIQUID FLOW RATE:</b>	
1. 0 m <sup>3</sup> /s	
2. 0.00063 m <sup>3</sup> /s	
3. 0.0013 m <sup>3</sup> /s	
4. 0.0019 m <sup>3</sup> /s	
5. 0.0025 m <sup>3</sup> /s	
6. 0.0032 m <sup>3</sup> /s	
Range of rotor speeds: 0 to 1000 rpm	
<b>CRITERIA FOR ACCEPTING A RUN:</b>	
<b>VARIABLE</b>	<b>ACCEPTABLE VARIANCE</b>
Rotor speed	±5 rpm
Liquid flow	±5% of set point
Gas flow	±5% of set point for 5 min

TABLE 6. MASS TRANSFER TEST CONDITIONS FOR THE CENTRIFUGAL STRIPPER

<b>PACKING DEPTH:</b>
4 inches
7 inches
10 inches
<b>ACCELERATION AT INNER RADIUS:</b>
1. 340 m/s <sup>2</sup> (500 rpm)
2. 549 m/s <sup>2</sup> (633 rpm)
3. 855 m/s <sup>2</sup> (790 rpm)
4. 1161 m/s <sup>2</sup> (921 rpm)
5. 1370 m/s <sup>2</sup> (1000 rpm)
<b>LIQUID FLOW RATE:</b>
1. 0.0013 m <sup>3</sup> /s
2. 0.0016 m <sup>3</sup> /s
3. 0.0022 m <sup>3</sup> /s
4. 0.0028 m <sup>3</sup> /s
5. 0.0032 m <sup>3</sup> /s
<b>GAS/LIQUID RATIO (vol/vol):</b>
1. 5.7 (S* = 1.2 for m-Xylene)
2. 7.5
3. 10.1 (S = 2.1 for m-Xylene)
4. 12.7
5. 14.4 (S = 3.0 for m-Xylene)
Variables to be monitored: Rotor speed, air flow rate, liquid flow rate, inlet-outlet gas and liquid temperature, and pressure drop.
Samples taken: Inlet and outlet liquid and outlet air. Exit liquid samples taken from the sample tube. All liquid samples were taken in duplicate.

**TABLE 6. MASS TRANSFER TEST CONDITIONS FOR THE  
CENTRIFUGAL STRIPPER (CONCLUDED)**

<b>COMPOUNDS ANALYZED:</b>	
1. Benzene	
2. 1,2,4-trimethylbenzene	
3. Methyl cyclohexane	
4. Pentane	
5. Toluene	
6. m-Xylene	
7. o-Xylene	
8. Naphthalene	
<b>CRITERIA FOR ACCEPTING A RUN:</b>	
<b>VARIABLE</b>	<b>ACCEPTABLE VARIANCE</b>
Rotor speed	$\pm 5$ rpm
Liquid flow	$\pm 5\%$ of set point
Gas flow	$\pm 5\%$ of set point for one hour
Temperature	$\pm 0.56^{\circ}\text{C}$

\*S = stripping factor.  $S = mG/L$ , where  $m = y/x$  and G and L are gas and liquid rates, respectively, in mol/s.



TABLE 7. CENTRAL COMPOSITE DESIGN FOR THE CENTRIFUGAL STRIPPER

Order	Acceleration (m/s <sup>2</sup> )	Water Flow (m <sup>3</sup> /s)	Gas To Liquid Ratio (vol/vol)	Rotor Speed (rpm)	Gas Flow (m <sup>3</sup> /s)
Packing depth = 4 inches					
1	855	0.0022	10.1	790	0.022
2	855	0.0013	10.1	790	0.013
3	855	0.0032	10.1	790	0.032
4	855	0.0022	10.1	790	0.022
5	340	0.0022	10.1	498	0.022
6	549	0.0028	12.7	633	0.035
7	855	0.0022	10.1	790	0.022
8	1161	0.0016	7.5	921	0.012
9	549	0.0016	7.5	633	0.012
10	855	0.0022	10.1	790	0.022
11	855	0.0022	5.7	790	0.013
12	1161	0.0028	12.7	921	0.035
13	855	0.0022	10.1	790	0.022
14	549	0.0028	7.5	633	0.021
15	1161	0.0028	7.5	921	0.021
16	855	0.0022	10.1	790	0.022
17	1370	0.0022	10.1	1000	0.022
18	855	0.0022	14.4	790	0.032
19	855	0.0022	10.1	790	0.022
20	1161	0.0016	12.7	921	0.021
21	549	0.0016	12.7	633	0.021
22	855	0.0022	10.1	790	0.022

TABLE 7. CENTRAL COMPOSITE DESIGN FOR THE CENTRIFUGAL STRIPPER (CONTINUED)

Order	Acceleration (m/s <sup>2</sup> )	Water Flow (m <sup>3</sup> /s)	Gas To Liquid Ratio (vol/vol)	Rotor Speed (rpm)	Gas Flow (m <sup>3</sup> /s)
Packing depth = 7 inches					
1	855	0.0022	10.1	790	0.022
2	1161	0.0028	12.7	921	0.035
3	855	0.0013	10.1	790	0.013
4	855	0.0022	10.1	790	0.022
5	1161	0.0016	7.5	921	0.012
6	855	0.0022	5.7	790	0.013
7	855	0.0022	10.1	790	0.022
8	549	0.0016	7.5	633	0.012
9	549	0.0028	12.7	633	0.035
10	855	0.0022	10.1	790	0.022
11	855	0.0022	14.4	790	0.032
12	1370	0.0022	10.1	1000	0.022
13	855	0.0022	10.1	790	0.022
14	855	0.0032	10.1	790	0.032
15	549	0.0016	12.7	633	0.021
16	855	0.0022	10.1	790	0.022
17	1161	0.0028	7.5	921	0.021
18	549	0.0028	7.5	633	0.021
19	855	0.0022	10.1	790	0.022
20	340	0.0022	10.1	498	0.022
21	1161	0.0016	12.7	921	0.021
22	855	0.0022	10.1	790	0.022

TABLE 7. CENTRAL COMPOSITE DESIGN FOR THE CENTRIFUGAL STRIPPER (CONCLUDED)

Order	Acceleration (m/s <sup>2</sup> )	Water Flow (m <sup>3</sup> /s)	Gas To Liquid Ratio (vol/vol)	Rotor Speed (rpm)	Gas Flow (m <sup>3</sup> /s)
Packing depth = 10 inches					
1	855	0.0022	10.1	790	0.022
2	549	0.0028	12.7	633	0.035
3	855	0.0013	10.1	790	0.013
4	855	0.0022	10.1	790	0.022
5	1161	0.0028	12.7	921	0.035
6	855	0.0022	5.7	790	0.013
7	855	0.0022	10.1	790	0.022
8	340	0.0022	10.1	498	0.022
9	549	0.0016	12.7	633	0.021
10	855	0.0022	10.1	790	0.021
11	1161	0.0028	7.5	921	0.021
12	549	0.0028	7.5	633	0.021
13	855	0.0022	10.1	790	0.022
14	549	0.0016	7.5	633	0.012
15	1161	0.0016	7.5	921	0.012
16	855	0.0022	10.1	790	0.022
17	855	0.0022	14.4	790	0.032
18	1161	0.0016	12.7	921	0.021
19	855	0.0022	10.1	790	0.022
20	1370	0.0022	10.1	1000	0.022
21	855	0.0032	10.7	790	0.032
22	855	0.0022	10.1	790	0.022

A regenerated carbon from the Calgon Company was used for the carbon adsorption tests. A carbon that has been regenerated several times was chosen to test a material representative of a typical carbon being utilized in the field.

The test conditions and the variables monitored are shown in Table 8. The detailed experimental design is shown in Table 9.

#### **4. Catalytic Destruction Unit**

The objectives of the experiments with the catalytic destruction unit were to demonstrate emissions control effectiveness, to generate data which could be used to make an economic comparison with activated carbon, and to determine if adverse effects on catalyst life resulted from utilization in this type of application. In air stripping service, catalyst life may be affected by carryover of water droplets and/or particles from the air stripper, and catalyst poisons such as sulphur in the groundwater.

The test conditions and the data collection requirements for the catalytic destruction unit are given in Table 10. Gas samples for side product formation analysis using GC/MS were to be taken at operating conditions where such product formation was likely to occur. In addition, a run at a selected set conditions was to be repeated periodically to determine if catalyst activity changed with operating time. For reasons discussed in the section on results, the latter two tests were not conducted.

### **B. EXPERIMENTAL PROCEDURES**

#### **1. Conventional Packed Column**

##### **a. Installation and Removal of the Random Packing**

Because several different type of packings were studied in the operation of the packed tower, it was necessary to install and remove packings. Because settling of random packings could occur during operation, proper precautions were taken during installation. Generation of reliable data required that the packing characteristics did not change significantly with time. The procedure utilized by Stallings and Rogers (Reference 26) in the installation of random packing was followed.

To load the column, the packing support plate was installed at the bottom of the column. The packing was loaded into the column to give a packing height of approximately 127 mm and then water was passed through the tower to help in compressing the packing. This procedure was repeated until the proper packing height was reached. The sample probe shields were installed just before the packing depth reached each sample tap. After the proper height of packing was reached, the distributor and the top section of the tower were installed.

TABLE 8. TEST CONDITIONS FOR THE ACTIVATED CARBON BED

<b>AIR TO WATER RATIOS (vol/vol) IN THE STRIPPER:</b>	
1.	6
2.	15
3.	40
<b>GAS FLOW RATE:</b>	
0.0047 m <sup>3</sup> /s	
<b>RELATIVE HUMIDITY:</b>	
1.	25 percent
2.	100 percent
Variables monitored: gas flow rate, relative humidity, temperature of the inlet gas stream, and inlet-outlet gas concentrations.	
Samples taken: inlet and outlet gas	
<b>COMPOUNDS ANALYZED:</b>	
1.	Benzene
2.	1,2,4-trimethylbenzene
3.	Methyl cyclohexane
4.	Pentane
5.	Toluene
6.	m-Xylene
7.	o-Xylene
8.	Naphthalene
<b>CRITERIA FOR ACCEPTING A RUN:</b>	
<b>VARIABLE</b>	<b>ACCEPTABLE VARIANCE</b>
G/L ratio	±5%
Relative humidity	±5% absolute over 8 hours

TABLE 9. EXPERIMENTAL DESIGN FOR THE ACTIVATED CARBON BED

Order	Gas-To-Liquid Ratio In Air Stripper (vol/vol)	Gas Flow (m <sup>3</sup> /s)	Relative Humidity (%)
1	15	0.0047	25
2	6	0.0047	100
3	6	0.0047	25
4	40	0.0047	25

TABLE 10. TEST CONDITIONS FOR THE CATALYTIC DESTRUCTION UNIT

<b>TYPES OF CATALYST:</b>	
1.	204°C Initiation temperature
2.	316°C Initiation temperature
<b>DEPTHS OF THE CATALYST BED:</b>	
1.	7.6 mm
2.	15.2 mm
<b>STRIPPING FACTOR IN THE STRIPPERS<sup>a</sup>:</b>	
1.	$S^b = 1.5$ for m-Xylene
<b>AIR FLOW RATE TO CATALYTIC UNIT:</b>	
1.	0.0028 m <sup>3</sup> /s
2.	0.0047 m <sup>3</sup> /s
<b>TEMPERATURE:</b>	
5 levels of temperatures. Values of temperatures are to be established after preliminary run with each type of catalyst. Depth of catalyst should be varied at one condition.	
Variable to monitor: gas flow rate, preheater metal temperature, and bed inlet and outlet temperature.	
Samples to be taken: preheater inlet and catalyst bed inlet and outlet.	
<b>COMPOUNDS TO BE ANALYZED FOR:</b>	
1.	Benzene
2.	1,2,4-trimethylbenzene
3.	Methyl cyclohexane
4.	Pentane
5.	Toluene
6.	m-Xylene
7.	Methyl butane
8.	Naphthalene

TABLE 10. TEST CONDITIONS FOR THE CATALYTIC DESTRUCTION UNIT (CONCLUDED)

CRITERIA FOR ACCEPTING A RUN:	
VARIABLE	ACCEPTABLE VARIANCE
Gas/liquid ratio in stripper	$\pm 10\%$
Gas flow to catalytic unit	$1.4 \times 10^{-4} \text{ m}^3/\text{s}$
Temperature	$\pm 2.8^\circ\text{C}$ at catalyst bed exit

<sup>a</sup>One additional experiment was conducted at an S of 3 for one set of conditions.

<sup>b</sup>S stripping factor.  $S = mG/L$ , where  $m = y^*/x^*$  and G and L are gas and liquid rates, respectively, in mol/s.



To remove the packing from the tower, the sample tubes which extended into the column, the upper section of the tower, and the distributor were removed. As much as possible, the packing material was scooped out, beginning at the top and working down. The tower was built in sections to facilitate this operation. The rest of the packing was removed by hoisting the column and dumping all the packing out the bottom. The packing was collected in a plastic sheet that had been placed around the bottom of the column. After all the packing material was removed, the tower section was cleaned with water to remove any precipitates or biological growth prior to reassembly and repacking.

**b. Installation and Removal of the Koch/Sulzer and the Koch Flexiramic® Structured Packings**

In contrast to the random packing, settling of the structured packings does not occur. The cylindrical elements of the Koch packings were made to the full diameter of the column. Successive elements were rotated by 90 degrees to each other. The Koch packings were provided with a flexible seal on the outer radius to ensure proper seal between the packing and the column. The packing was lowered one section at a time into the column. Each section was pressed into place so that there was no free space between the different sections. Samples were not taken from the packed region of the column due to concerns about affecting the liquid flow distribution. The sample taps in the packed region were capped for these tests.

To unload the structured packings, the top of the column and the distributor were first removed. The Koch/Sulzer packing was forced out the top of the column by passing air up through the column at a high velocity. The Flexiramic® packing was removed through the bottom of the column. Detailed installation and removal procedures, as provided by Koch, were followed.

**c. Installation and Removal of the Delta SH Structural Packing**

Installation of the Delta SH packing was similar to that of the Koch packings. The packing sections were 0.305 meters high and were made to the full diameter of the column. There were no other necessary orientations for installation. Each section was pressed into place so that there was no free space between the different sections.

**d. Hydraulic Tests**

The purpose of the hydraulic tests was to determine the pressure drop behavior as a function of air and water loadings and compare the results with existing correlations. The tests were to be conducted at each liquid rate by first determining the " $F_*$ " value corresponding to a pressure drop of 800 Pascals/meter. The  $F_*$  parameter is defined by:

$$F_g = (\text{Superficial Gas Velocity}) (\text{Gas Density})^{1/2} \quad (56)$$

Development of correlations of tower pressure drop versus  $F_g$  is common industrial procedure. The  $F_g$  values for the other tests at the established liquid rate were at 1/4, 1/2, and 3/4 of the  $F_g$  corresponding to a pressure drop of 800 Pascals/meter.

#### **e. Mass Transfer Tests**

If necessary, the first step in the mass transfer tests was to start the groundwater well pumps (in most cases, the pumps had been operating for a long time) and allow the well pumps to run for 30 minutes to purge the well and well lines. The purge water was routed directly to the existing aeration basin. The purpose of this purging was to eliminate particulate matter from the well and to prevent contamination of the feed tank and column packing by oils and greases that may have gathered in the well during the time when the well was not being pumped. If this purging had not been carried out, the water from the well during this period may not have been representative of the VOC concentration in the aquifer. Once purging was completed, flow to the surge tank was initiated (if the surge tank contained water from the previous day, it was emptied before filling). After the surge tank was filled and was overflowing, feed to the stripper column was supplied from the bottom of the surge tank. Once the desired liquid flow rate to the stripper was achieved and the wet well at the stripper bottom was filled to the proper level, the air flow to the column was started. This was accomplished by starting the blower and adjusting the throttle valve until the desired flow of air through the column was reached. The air flow rate was indicated by the pressure drop reading from the calibrated orifice meter. The contaminant concentration in the effluent air from the stripper was monitored by an on-line total hydrocarbon analyzer (THA). When steady-state conditions were indicated by a constant reading of the total hydrocarbon analyzer, liquid samples were collected.

When collecting liquid samples, care was taken to avoid an excessive amount of contact between the liquid samples and air, since some of VOCs could be removed and, consequently, the samples would not represent the conditions in the tower. Liquid samples were collected into prelabeled 40 mL glass bottles (obtained from IChem Corp.) which contained 0.5 mL of 50 percent NaOH. The NaOH was added to minimize the adsorption of the VOCs on the glass surface, as discussed later. All sample taps from the unit were allowed to run continuously at a rate of approximately 250 mL/minute in order to collect representative samples. Stripping of the VOCs during the filling of the bottle was minimized by directing the stream from the reservoir against the inside wall of the bottle (Reference 26). The sample bottle was completely filled until it overflowed

and then it was sealed with a Teflon® septum cap. The bottles were checked for the absence of air bubbles, shaken for 30 seconds, and placed in a refrigerator until analysis. The sample bottles were used only once and then discarded.

## **2. Centrifugal Stripper**

### **a. Changing the Rotors**

Since the centrifugal stripper tests employed several different size rotors, it was necessary to change these rotors during the course of tests. Vendor procedures were followed.

### **b. Rotor Speed Calibration Curve**

The centrifugal stripper was equipped with a variable speed motor powered by a variable frequency inverter. A frequency setting versus rotor speed curve was determined for the unit. This calibration curve was generated using a strobe light to determine rotor speed as the setting of the variable frequency drive was changed. The calibration curve included a rotor speed range from 100 rpm to the maximum stable rotor speed possible, in 100 rpm intervals.

### **c. Hydraulic Tests**

The hydraulic tests (Reference 33) with the centrifugal stripper were similar to those with the conventional packed column, and were done on each of the three rotors. A hydraulic run was started by setting the rotor speed at 1000 rpm and then establishing the liquid and gas flows at the desired values. After three minutes, the pressure drop across the packing and the power consumption were measured. The rotor speed was then decreased by 100 rpm and the two dependent variables remeasured. This procedure was repeated until either the desired air flow rate could not be maintained because of high pressure drop or the inside eye of the rotor filled with water.

### **d. Mass Transfer Tests**

For the mass transfer tests (Reference 33) with the centrifugal stripper, mass transfer coefficients were determined as a function of packing depth. As pointed out previously, this was accomplished by using three different size rotors. Because it was difficult to change rotors, data were taken on one rotor at a time. Thus, the experiments were of a block design. The liquid flowrate, gas-to-liquid ratio, and rotor speed were randomized within each block.

The procedures for setting the liquid and air flow rates to the centrifugal stripper were similar to those described for the packed column stripper. A mass transfer experiment was initiated by setting the rotor speed at the indicated value and then starting liquid flow to the stripper. After the liquid flow rate had stabilized, air flow was started to the stripper. When the exit air stream VOC concentration had reached a steady-state value, as indicated by the THA reading, the liquid samples

were collected. The liquid samples were taken in a manner similar to that for the packed column stripper. The samples of water exiting the rotor were taken from the sample tube positioned at the outer edge of the rotor. Samples were taken of the liquid leaving the rotor housing to see if additional stripping of VOC's was occurring.

### **3. Activated Carbon Bed**

The carbon bed canister was loaded by placing the empty container on a scale and loading the desired amount of carbon into the canister (a particle mask was worn during the loading and unloading of the canister). After the carbon had been loaded with VOCs, the canister was removed from the system and emptied. Because the loaded carbon was considered a hazardous material, it was kept in a stainless-steel drum until proper disposal.

The first step in the testing of the activated carbon emissions control system was to bring the bed to the experimental temperature by passing ambient air through the preheater and into the bed while adjusting the external heaters on the bed to minimize heat loss. At the same time, the air stripper was brought to steady-state operation at the desired experimental conditions. Next, the ambient air supply to the carbon bed was shut off and a portion of the exhaust air from the stripper was routed through a flow meter to the activated carbon system. The temperature of the air from the stripper to the carbon bed was automatically controlled to obtain the desired humidity level. The exit stream from the carbon bed was then monitored using the total hydrocarbon analyzer and the gas chromatograph to determine the breakthrough curve.

For some tests, the bed canister was filled with molecular sieve material instead of activated carbon. Experimental procedures and data output were similar to those when activated carbon was used.

### **4. Catalytic Destruction Unit**

When necessary to change the catalyst, the insert, in which the catalyst was installed, had to be removed from the reactor body. When the reactor was at ambient temperature, the insert was removed by loosening the large nut which secured the insert to the reactor body, and then lowering the insert from the body. The used catalyst was then replaced with a new catalyst. Up to three of the 76 mm long catalyst sections could be placed in the insert. To eliminate bypassing between the catalyst and the wall of the insert, the catalyst sections were wrapped with a thin layer of high-temperature insulation before the sections were placed into the insert. The insert was then reinstalled in the reactor body and secured by tightening the large nut.

To perform a test on the catalytic destruction unit, the first step was to introduce ambient air at the desired flow rate by adjusting the flowmeter valve. The ambient air was then heated to the desired control temperature set point before introduction of the effluent stream to be abated. This was necessary to prevent condensation of organic high boiling point compounds on the catalyst and subsequent coking. The preheater temperature was controlled to provide the desired temperature of the inlet air to the catalyst bed. The heaters on the catalyst shell were adjusted to minimize heat loss. When operating conditions had reached steady state, the ambient air flow was shut off and the stripper effluent was routed to the catalytic unit. Conversions of the VOCs in the preheater and across the catalyst bed were then determined by injecting gas samples from the stripper effluent, the preheater outlet, and the catalyst bed outlet into the GC for analysis.

### C. ANALYTICAL PROCEDURES

#### 1. Chemical Characterization of Groundwater

The contaminated groundwater was sampled and analyzed for the following: VOCs, base/neutrals, iron, manganese, hardness, pH, total organic carbon, inorganic carbon, total dissolved solids, total suspended solids,  $H_2S$ , and alkalinity. Standard methods were used for all the analyses. In addition, Henry's Law constants for selected organic compounds were determined using the modified EPICS method described by Singh (Reference 34).

Based upon the results of a previous analysis for VOCs by gas chromatography/mass spectroscopy (GC/MS), eight components were studied in these experiments. These compounds, and their Henry's Law constants at 25°C (Reference 35), are shown below.

COMPOUNDS	HENRY'S LAW CONSTANT (atm/mol fraction)
Pentane	68,550
Methyl cyclohexane	21,936
m-Xylene	384
Toluene	367
1,2,4-Trimethylbenzene	324
Benzene	302
o-Xylene	274
Naphthalene	24

The Henry's Law constants at other temperatures may be obtained from correlations, such as discussed later.

Reasons for choosing these specific compounds were:

1. Benzene was chosen because the Environmental Protection Agency regulations are based on this compound.
2. Pentane was chosen because this compound is difficult to destroy in the catalytic destruction unit. Methyl butane had been chosen initially, but problems were encountered with its analysis.
3. Methyl cyclohexane was chosen because there is not much known about its behavior in the catalytic destruction unit.
4. The other compounds were chosen because of the concentration present in the groundwater and the availability of physical properties data.

## **2. Analysis of Samples**

Because of the sensitivity of the analysis procedure for VOCs to the technique used in handling samples, and of the numerous problems which can be encountered in a field laboratory, the Air Force required, in the Statement of Work for the project, that all field analyses were to be performed by a chemist familiar with the purge and trap method. Maecorp Inc. (Caledonia, Michigan) was subcontracted to provide personnel to perform liquid and gas analyses utilizing the equipment described previously.

### **a. Development of Analytical Procedures**

Prior to shipment of the analytical equipment to Eglin Air Force Base, the analytical system was set up and checked out by the Quality and Technical Services Division at the Oak Ridge Gaseous Diffusion Plant (ORGDP). The system was fine-tuned for the compounds that were present in the groundwater at a petroleum, oils, and lubricants (POL) site on Eglin Air Force Base. The method used for analysis of VOCs in the liquid samples was similar to EPA Method 602, with the exception that an external standard was not used. During operations at Eglin Air Force Base, the temperature program of the GC oven was modified in order to decrease run time and to completely elute late peaks. The oven of the GC was programmed as follows: start at 40°C and hold for 6 minutes; increase at a rate of 3°C/minute to 135°C and hold for 0.01 minute; increase at the rate of 25°C/minute to 180°C and hold for 4 minutes.

During checkout of the analytical equipment at the ORGDP, the recovery of some compounds (particularly the aromatics) from the low concentration standards was observed to vary significantly when triplicate samples were analyzed. The effect was a function of time. That is, when

three samples of the same concentration were loaded at the same time on the ALS and then analyzed sequentially by the GC, the measured recovery decreased with each succeeding analysis. After experimentally eliminating several possibilities that could cause the apparent loss of volatile compounds (leaks, biological activity, photo-degradation), it was postulated that the organic compounds may be adsorbing on the surfaces of the glass sparge tubes of the ALS. Frit sparge tubes were being used on the ALS at the time, which would exacerbate the problem due to the large surface area of the frit. It was suggested that the adsorption sites could be tied up by adding sodium hydroxide to the samples. After changing the standards to a basic solution and replacing the frit sparge tubes with needle sparge tubes to minimize surface area, no further changes in recovery with time were observed. Consequently, during the field tests, all calibration standards were prepared using basic solutions, and NaOH was added to the 40 mL sample bottles before withdrawing water samples from the air strippers.

#### **b. Preparation of Standard Solutions**

At the field test site at Eglin Air Force Base, the gas chromatograph was calibrated using standards containing 1, 50, 100, and 500 ppb of each compound of interest. The standards were prepared by diluting a stock solution which contained 1000 ppb of each compound in methanol. The water used for diluting the samples and standards was prepared by passing tap water through an activated carbon filter. Fresh stock solutions were prepared once a month by ORGDP analytical personnel and shipped to the test site. The amount of each compound in the stock solution was accurately determined using an analytical balance.

#### **c. Liquid Samples**

Before loading the liquid samples on the ALS automatic sampler, the sample bottles were removed from the refrigerator and allowed to come to room temperature. When the samples had reached room temperature, a 5 mL aliquot was placed into needle sparge tubes and the tubes were immediately attached to the ALS sampler. For the stripper tests, the liquid from each sample bottle was analyzed in duplicate to ensure greater reliability of the final results. Initially, duplicate samples were taken and each duplicate was analyzed. However, the results from the duplicates demonstrated unacceptably large variances. The addition of NaOH to the sample bottles caused precipitation of iron hydroxide. Apparently, the precision problem was caused by adsorption of VOCs on the precipitate. The decision was made to analyze one sample bottle from each sample point in duplicate, taking care to insure the precipitate was well mixed before withdrawing the 5 mL sample for the ALS. This resulted in an acceptable variance level.

A quality control program consisting of the following measures was also implemented. A blank sample, which was prepared by passing tap water through an activated carbon bed, was analyzed with each set of three samples from a particular run. The separation and identification of the peak on the chromatogram was ensured by spiking certain samples with a standard solution. The proper functioning of the equipment was also checked by running standard samples. When the relative error from the standard and spiked samples was greater than 10 percent, steps were taken to isolate and correct the problem.

#### **d. Gas Samples**

The gas sampling system is shown in Figures 17 through 19. Four gas samples from the air stripping system and a calibration standard were connected to a sample valve box, as shown in Figure 17. Each of the lines from the stripping system was equipped with a pump. Under normal operating conditions, the gas flowed through the valve box and out to the atmosphere. When a gas sample for the GC was required, the appropriate three-way solenoid valve was energized to send the gas to the GC sample valve oven. The GC sample valve oven contained a six-port sampling valve, shown in Figure 18, with an actuator. During the purging phase, the sample gas flowed into port 1 and out of port 2 to the atmosphere, and helium flowed into port 5 and out of port 6 to the ALS. When the sampling valve was actuated, the sample gas flowed to the ALS and the helium was vented. In order to utilize the ALS for gas samples, the liquid sample tube was removed from one of the ten stations and the ALS helium purge line to that station was capped. The gas sample line from the GC sampling valve was attached to the connection at that station normally used for the liquid sample tube outlet. Thus, the sample gas was routed directly through the ALS and to the Tenax® trap which was installed in the LSC.

At the same time that the GC sample valve was actuated, a valve on the LSC vent line, shown in Figure 19, was closed. As seen in Figure 19, the gas sample was caused to flow from the GC sample valve, through the ALS, to the Tenax® trap (on which the hydrocarbons were adsorbed) installed in the LSC, and to a 400-mL burette which was initially filled with water. When the water was displaced from the burette, the vent valve was opened and the GC sampling valve was returned to its original position. The volume of water displaced from the burette was measured to determine the volume of gas sampled. The hydrocarbons collected from the gas sample on the Tenax trap were then injected into the GC for analysis by the same procedure as used when hydrocarbons were purged from a liquid sample on the ALS and collected on the Tenax® trap. The sample streams from the



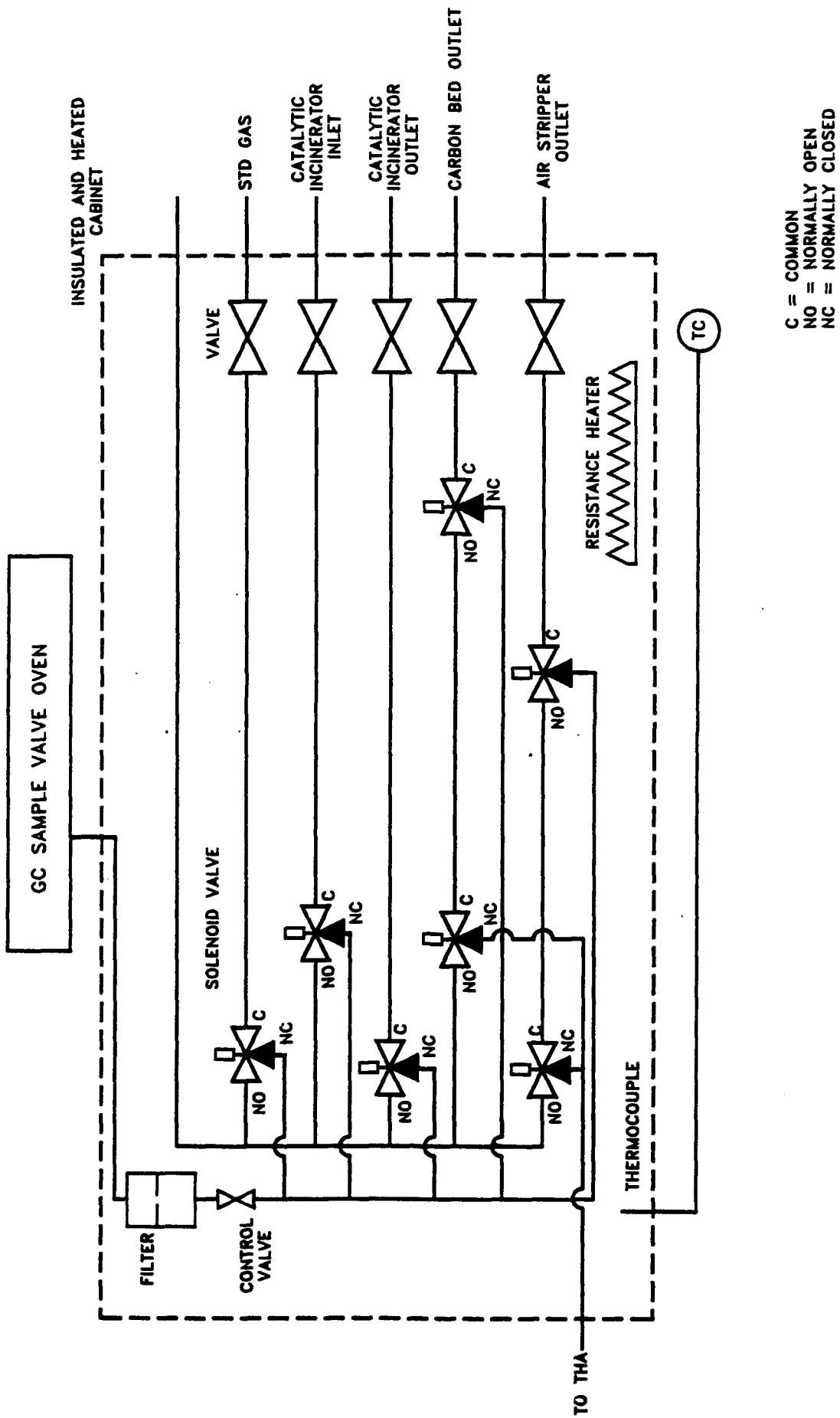


Figure 17. Gas Sampling Box.

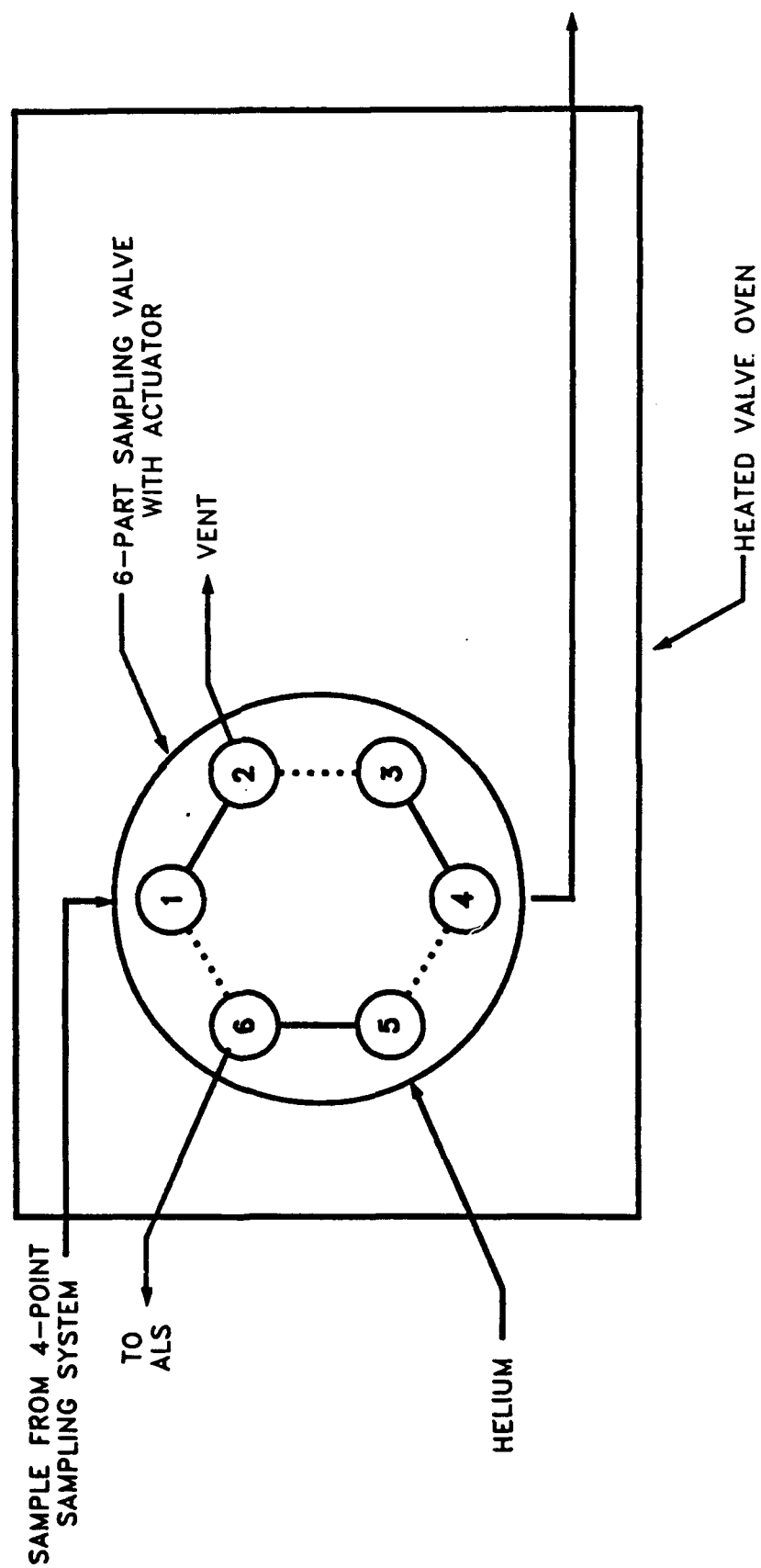


Figure 18. Sample Valve for Lab GC.

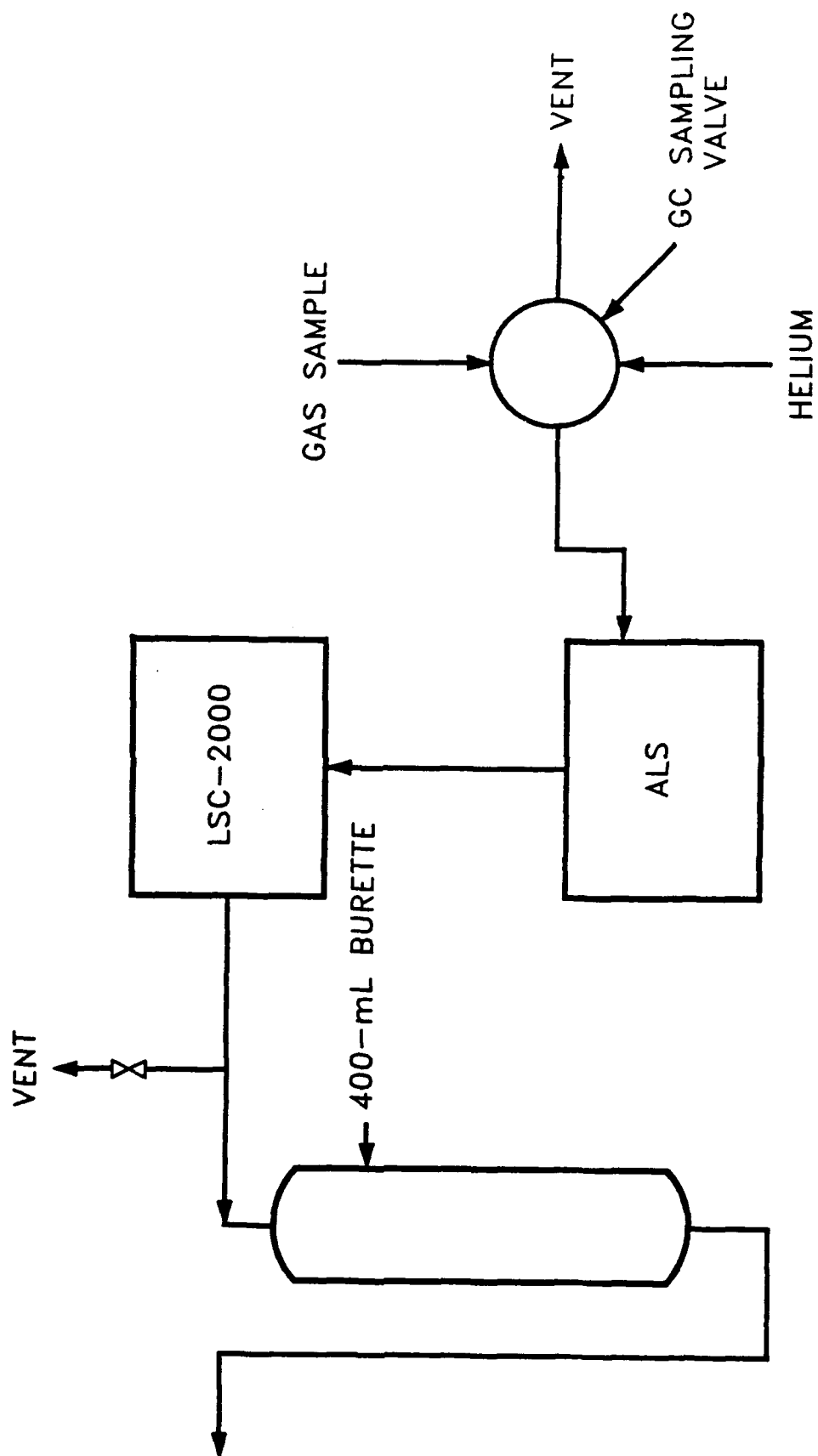


Figure 19. Schematic of Gas Sampling System for On-Line GC Analysis.

air stripper effluent and the carbon bed effluent could also be diverted to the total hydrocarbon analyzer, as shown in Figure 17. In order to prevent condensation, all gas sample lines were heat traced. The temperature of the gas sample lines was controlled to keep the gas below 100 percent humidity.

As discussed in the project test plan, a system was designed to measure low concentrations of hydrocarbons. The purpose was to check for possible products of incomplete combustion in the catalytic incinerator. However, because of the problems encountered, as described later, this sampling system was not utilized.

## SECTION V

### ANALYSIS OF GROUNDWATER

A typical analysis of the general chemical characteristics of the groundwater feed to the experimental system used on this activity is given in Table 11. Other analysis conducted over the course of the experimental activities showed these general characteristics remained fairly constant. Some general characteristics of the groundwater were: (1) pH = 5.5; (2) TOC = 11 mg/L; (3) TIC = 29 mg/L; (4) Fe = 8.4 mg/L; and (5) Hardness = 49 mg/L. After deactivation of the catalyst for control of gaseous VOCs, the groundwater was again analyzed for sulfur using a Hach kit. These analysis showed the groundwater to contain from 250 to 750 ppb of sulfur.

TABLE 11. ANALYSIS OF GROUNDWATER FEED TO EXPERIMENTAL SYSTEM (APRIL 1989)

COMPONENT	ANALYSIS (mg/L)
Alkalinity	33
Aluminum	<0.020
Barium	0.0096
Beryllium	<0.00030
Boron	0.018
Cadmium	<0.0030
Calcium	15
Chloride IC	93
Chromium	<0.010
Cobalt	<0.0050
Copper	<0.0040
Dissolved Solids	180
Fluoride FIA	<0.10
Iron	8.4
Lead	<0.050
Lithium	<0.0040
Magnesium	1.7
Manganese	0.069
Molybdenum	<0.010
Nickel	<0.010
Niobium	<0.0070
Nitrate	<1
Phosphorus	0.63
Potassium	2.5

**TABLE 11. ANALYSIS OF GROUNDWATER FEED TO EXPERIMENTAL  
SYSTEM (APRIL 1989) (CONCLUDED)**

<b>COMPONENT</b>	<b>ANALYSIS (mg/L)</b>
Silicon	2.0
Silver	<0.0060
Sodium	36
Strontium	0.044
Sulfate	7
Sulfide Volumetric	<1.0
Suspended Solids	24
Thorium	<0.20
Titanium	<0.0030
Total Inorganic Carbon (TIC)	29
Total Organic Carbon (TOC)	11
Total Phosphate	0.5
Total Residual Chlorine Vol	<0.02
Vanadium	<0.0050
Zinc	0.0047
Zirconium	<0.0050
pH FIA	5.5
Hardness	49

## SECTION VI

### RESULTS OF EXPERIMENTS

#### A. CONVENTIONAL PACKED-COLUMN AIR STRIPPER

The objective of these experiments was to determine the hydraulic characteristics and the overall  $H_{iOL}$  as a function of liquid rate and stripping factor for each of the packings tested. The method of  $H_{iOL}$  and  $H_L$  calculation is presented in Sections II and III. In the following discussion for each packing, some of the problems associated with running the experiments and the solutions to these problems are described before presenting the results.

##### 1. Flexirings®

While the hydraulic tests were being conducted with the Flexirings®, it was noticed that the total pressure drop across the packed bed when operating with groundwater was higher than that observed at similar conditions with tapwater. Also, at column liquid rates of 24.2 kg/m<sup>2</sup>-second or higher, the pressure drop tended to oscillate and foam was observed in the sight glass below the packed section of the column. These phenomenon were not observed with tap water nor with groundwater when using the structured packings. Apparently, the pressure oscillations were caused by foaming of the groundwater. Data from an experiment where this effect was evident is shown in Figure 20. To minimize the possible effect of foam on the mass transfer tests, the maximum liquid flow was chosen so that no pressure drop oscillations were observed. The pressure drop observed when tapwater was used compared well with published data; this indicates that the tower was packed correctly. The pressure drop tests with both tapwater and groundwater are shown in Figure 21. The straight lines were fit to the data by regression analysis. Although the pressure drop oscillations were minimized, the groundwater still appeared to exhibit a somewhat higher pressure drop than tap water.

During the mass transfer tests, a comparison of the VOC concentration in the water exiting the wet well to the VOC concentration immediately below the packing indicated that some mass transfer was occurring in wet well. Therefore, throughout the experiments for all of the packings tested, the concentration in the wet well outlet water stream was measured. Using these concentrations, the inlet air concentration to the packed section could be calculated from a material balance.



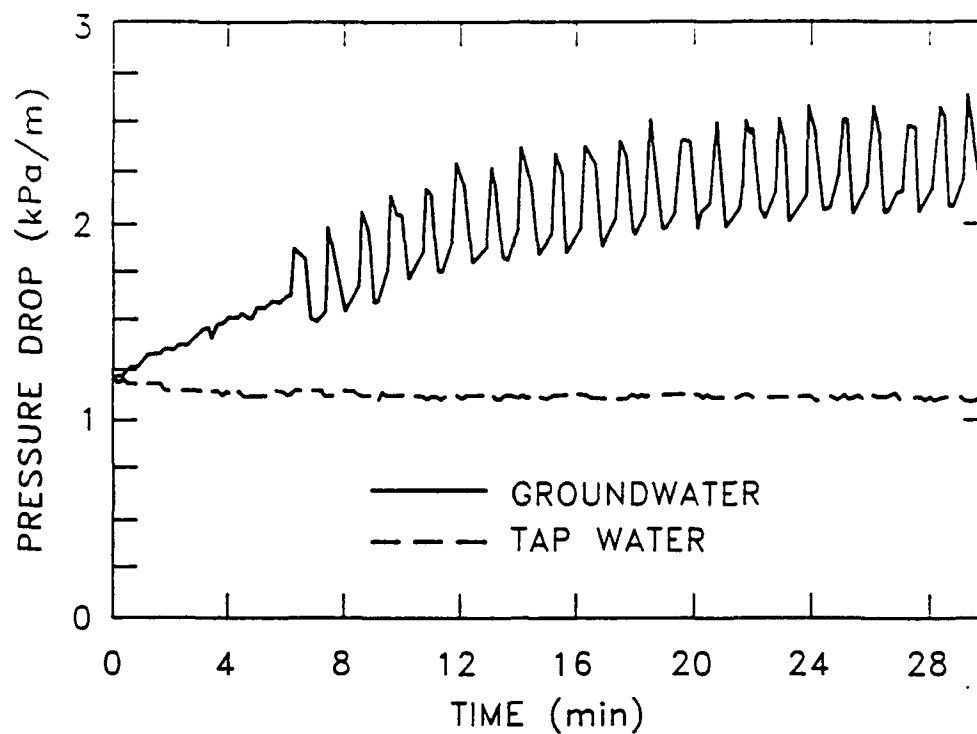


Figure 20. Total Pressure Drop Data for Similar Experiments using Groundwater and Tapwater.

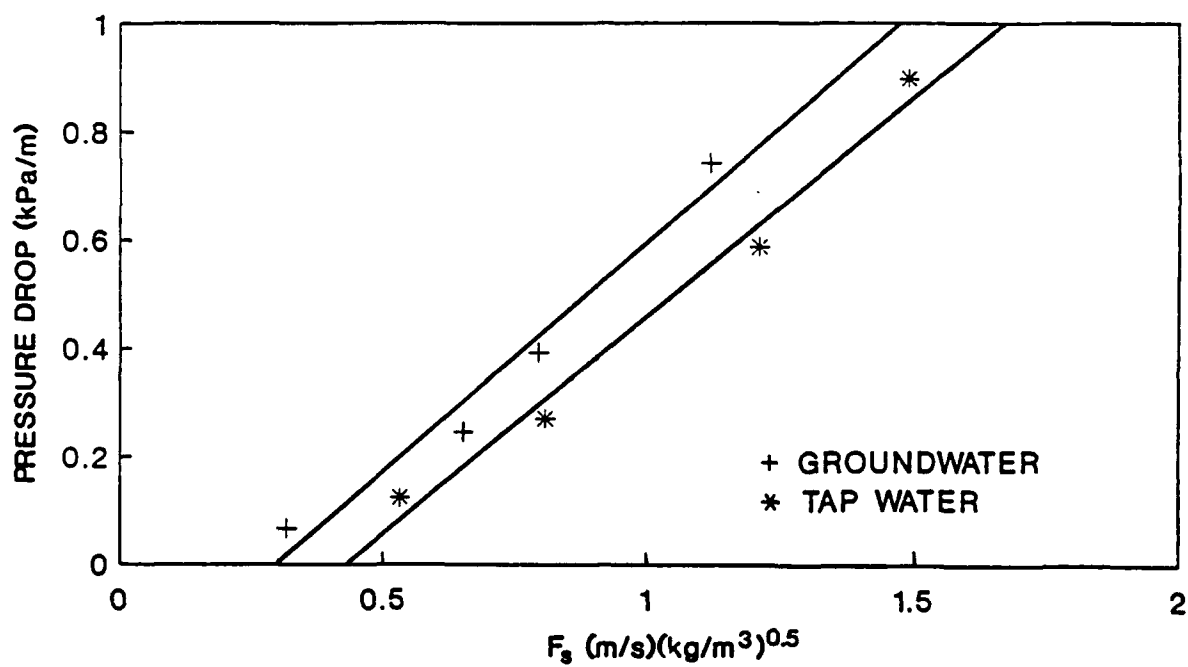


Figure 21. Comparison of Total Pressure Drop Data for Groundwater and Tapwater at a Liquid Rate of  $5.25 \text{ kg/m}^2\text{s}$ .

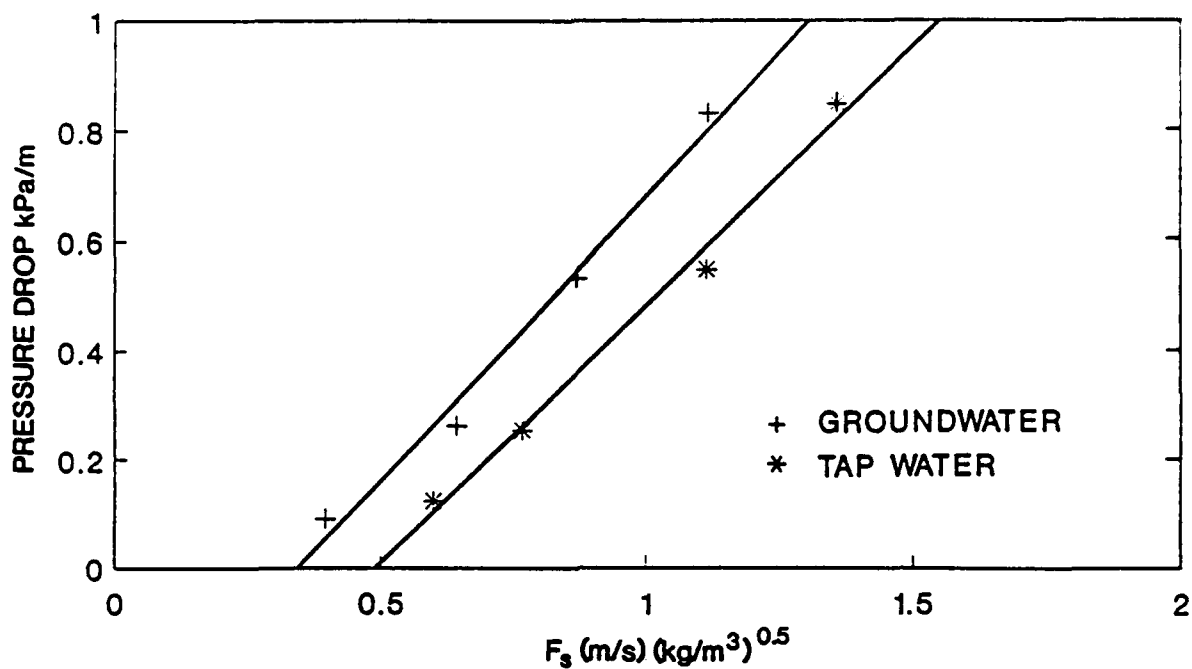


Figure 21. Comparison of Total Pressure Drop Data for Groundwater and Tapwater at a Liquid Rate of 6.9 kg/m<sup>2</sup>s. (Continued)

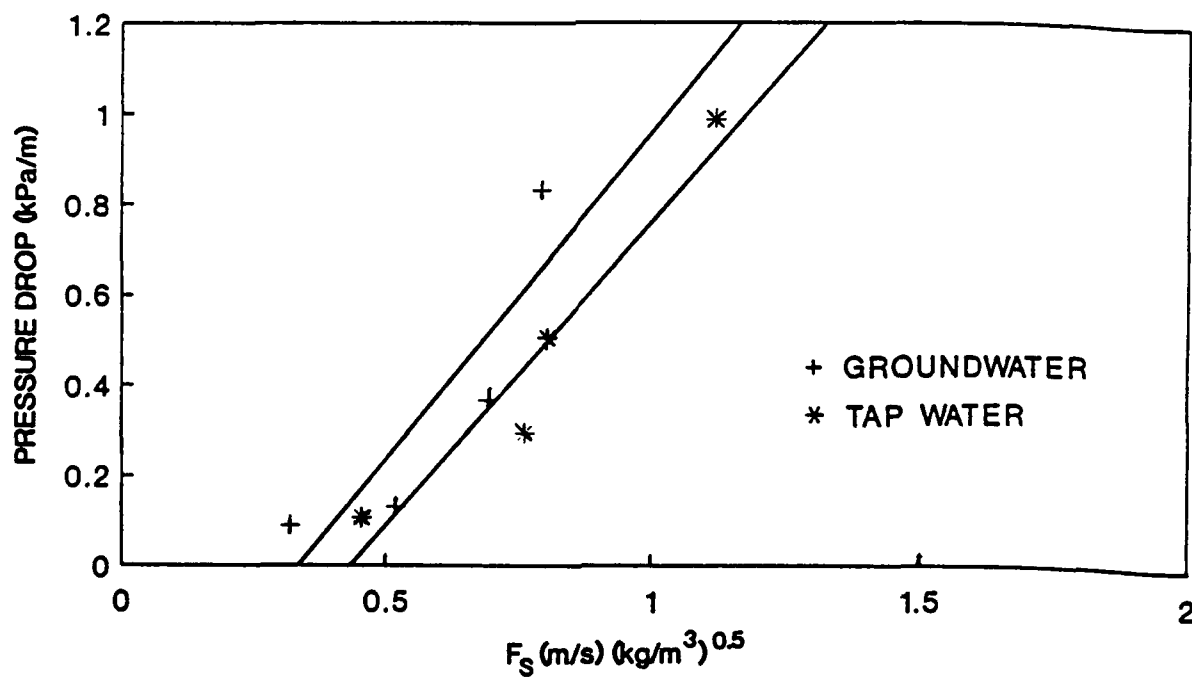


Figure 21. Comparison of Total Pressure Drop Data for Groundwater and Tapwater at a Liquid Rate of 10.7 kg/m<sup>2</sup>s. (Continued)

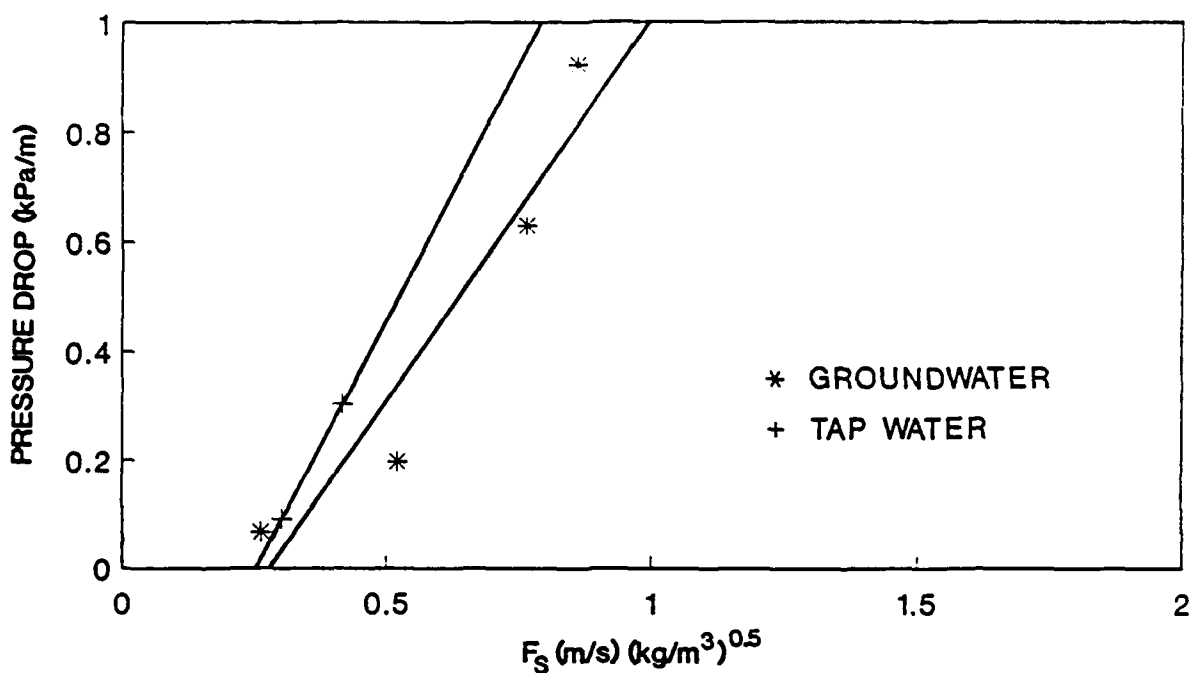


Figure 21. Comparison of Total Pressure Drop Data for Groundwater and Tapwater at a Liquid Rate of 14.9 kg/m²s. (Continued)

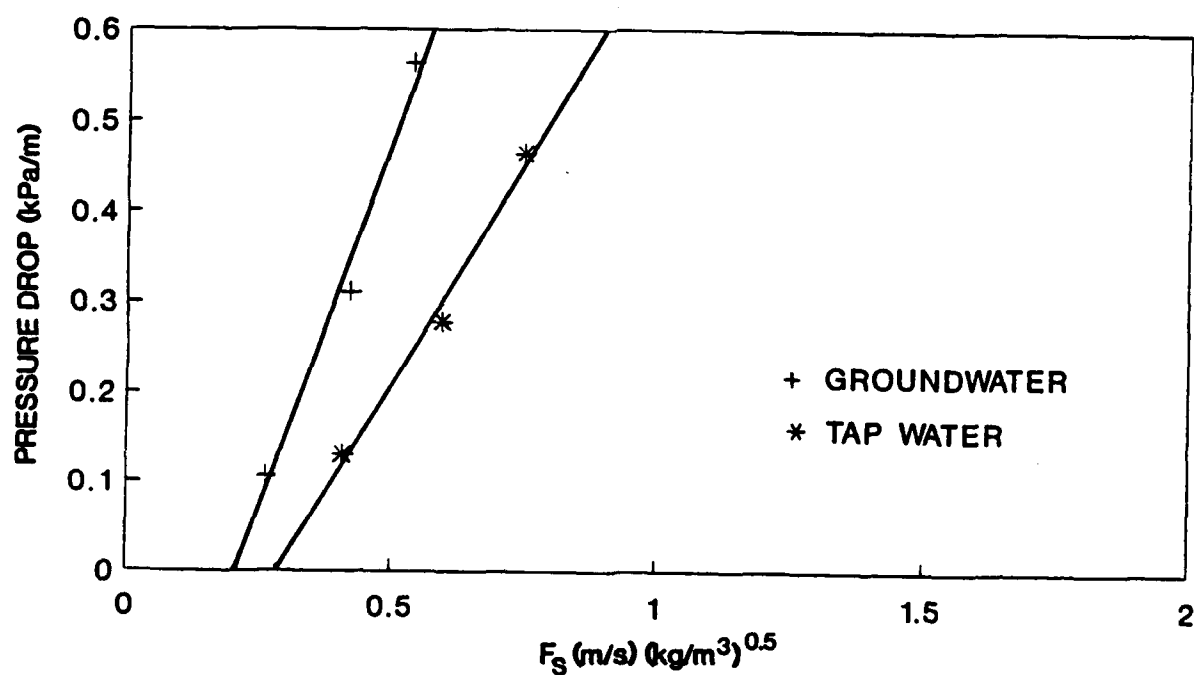


Figure 21. Comparison of Total Pressure Drop Data for Groundwater and Tapwater at a Liquid Rate of 16.2 kg/m²s. (Concluded)

The experimental  $H_{iOL}$  values for the 16 mm Flexirings® are shown in Table 12. To determine the experimental error and to check for packing degradation with time, the center point of the experimental design was periodically repeated during the experiments. The variation in the centerpoints is shown in Figure 22. While the centerpoint values tended to show some scatter, they did not change significantly for this series of experiments.

No general trend was evident in the data with respect to liquid rate over the range of flow conditions tested. However, some compounds showed evidence of an increase in  $H_{iOL}$  at low stripping factors as shown in Figure 23, which present the  $H_{iOL}$  values as a function of the stripping factor. As seen later, however, these same compounds did not show a similar increase in the runs with tapwater. Harriott (Reference 20) had noted such increases in  $H_{iOL}$  at low stripping factors in an examination of data from Gossett et al. (Reference 36), and concluded that the effect was caused by liquid maldistribution. This conclusion is not supported by the data presented here. The reasoning is that, if the increase in the  $H_{iOL}$  was actually due to liquid maldistribution, then all other compounds with approximately the same stripping factor would exhibit the same increase. Examination of the data revealed that, at low stripping factors, the gas concentrations exiting the tower were approaching equilibrium with the liquid concentrations entering the tower. That is, the number obtained by dividing the exit gas concentration by the dimensionless Henry's Law constant approached the inlet liquid concentration. Since the calculation of  $N_{iOL}$  is very sensitive to the stripping factor close to equilibrium, the experimental uncertainties in the stripping factor values could account for the apparent increase in  $H_{iOL}$  in some cases.

The tendency of the groundwater to foam, as observed in the hydraulic tests for Flexirings®, raises the question of whether the data might be site specific. Three methods were tested to check the usefulness of the data for general design purposes. As discussed in Section IV, the Henry's Law constants for each compound studied were measured using a modified EPICs method (Reference 36) and compared to literature values. This comparison indicated reasonable agreement between the literature and experimental values. Several tests were also run with a synthesized solution of ortho-xylene and meta-xylene in tapwater. The results from the tapwater runs are shown in Table 13, and compared to the groundwater tests in Figure 24. The  $H_{iOL}$  was slightly lower for tapwater than groundwater, but the temperatures of the tapwater tests were 8 to 10°C higher than those of the groundwater tests. This largely accounts for the difference in the  $H_{iOL}$  values. A "t" test between the means of the two sets of data, however, showed no difference at a 95 percent confidence interval. The tests using groundwater were also compared to the test using tapwater by normalizing the

TABLE 12. OVERALL EXPERIMENTAL HEIGHTS OF TRANSFER UNITS FOR 16-mm FLEXIRINGS®

Run #	Liquid Rate kg/m <sup>2</sup> -s	Gas Rate kg/m <sup>2</sup> -s	Ortho-Xylene		Benzene		Methylcyclohexane		Toluene	
			Stripping Factor	H <sub>OL</sub> (m)	Stripping Factor	H <sub>OL</sub> (m)	Stripping Factor	H <sub>OL</sub> (m)	Stripping Factor	H <sub>OL</sub> (m)
1	10.6	0.137	1.66	0.83	1.81	0.55	165.36	0.63	2.17	0.63
2	15.1	0.109	0.98	1.11	1.07	0.60	91.49	0.59	1.28	0.64
3	16.6	0.214	1.72	0.91	1.87	0.64	164.37	0.61	2.24	0.71
4	10.7	0.138	1.74	0.69	1.89	0.54	163.79	0.63	2.26	0.61
5	5.3	0.071	1.82	0.95	1.97	0.68	172.50	0.82	2.36	0.92
6	10.5	0.059	0.74	2.07	0.80	0.68	71.15	0.68	0.96	0.80
7	10.9	0.133	1.62	0.90	1.76	0.62	155.16	0.65	2.11	0.73
8	6.7	0.128	2.55	0.83	2.77	0.60	242.41	0.80	3.32	0.62
9	10.9	0.218	2.68	0.80	2.91	0.60	253.63	0.68	3.49	0.62
10	11.0	0.136	1.67	0.81	1.82	0.57	156.51	0.64	2.18	0.64
11	15.0	0.266	2.42	0.84	2.63	0.62	224.02	0.63	3.15	0.68
12	6.7	0.052	1.05	0.305	1.14	0.23	97.77	0.64	1.37	0.34
13	10.7	0.137	1.76	0.72	1.91	0.52	162.49	0.64	2.28	0.58

Note: Packed height = 3.05 meters and tower cross-sectional area = 0.078 m<sup>2</sup>.

TABLE 12. OVERALL EXPERIMENTAL HEIGHTS OF TRANSFER UNITS FOR 16-mm FLEXIRINGS® (CONCLUDED)

Run #	Liquid Rate kg/m <sup>2</sup> -s	Gas Rate kg/m <sup>2</sup> -s	Meta Xylene		1,2,4-Trimethylbenzene		Naphthalene	
			Stripping Factor	H <sub>OL</sub> (m)	Stripping Factor	H <sub>OL</sub> (m)	Stripping Factor	H <sub>OL</sub> (m)
1	10.6	0.137	2.33	0.74	2.52	0.98	0.18	
2	15.1	0.109	1.38	0.89	1.40	1.28	0.10	
3	16.6	0.214	2.41	0.83	2.51	1.05	0.18	
4	10.7	0.138	2.44	0.68	2.50	0.81	0.18	
5	5.3	0.071	2.55	0.77	2.63	0.89	0.19	
6	10.5	0.059	1.04	1.01	1.09	1.54	0.08	
7	10.9	0.133	2.27	0.76	2.37	0.93	0.17	
8	6.7	0.128	3.58	0.70	3.69	0.76	0.26	
9	10.9	0.218	3.76	0.69	3.87	0.77	0.27	
10	11.0	0.136	2.35	0.65	2.39	0.73	0.17	
11	15.0	0.266	3.40	0.71	3.42	0.79	0.24	
12	6.7	0.052	1.48	0.36	1.49	0.40	0.11	
13	10.7	0.137	2.47	0.57	2.48	0.61	0.17	

Note: Packed height = 3.05 meters and tower cross-sectional area = 0.078 m<sup>2</sup>.

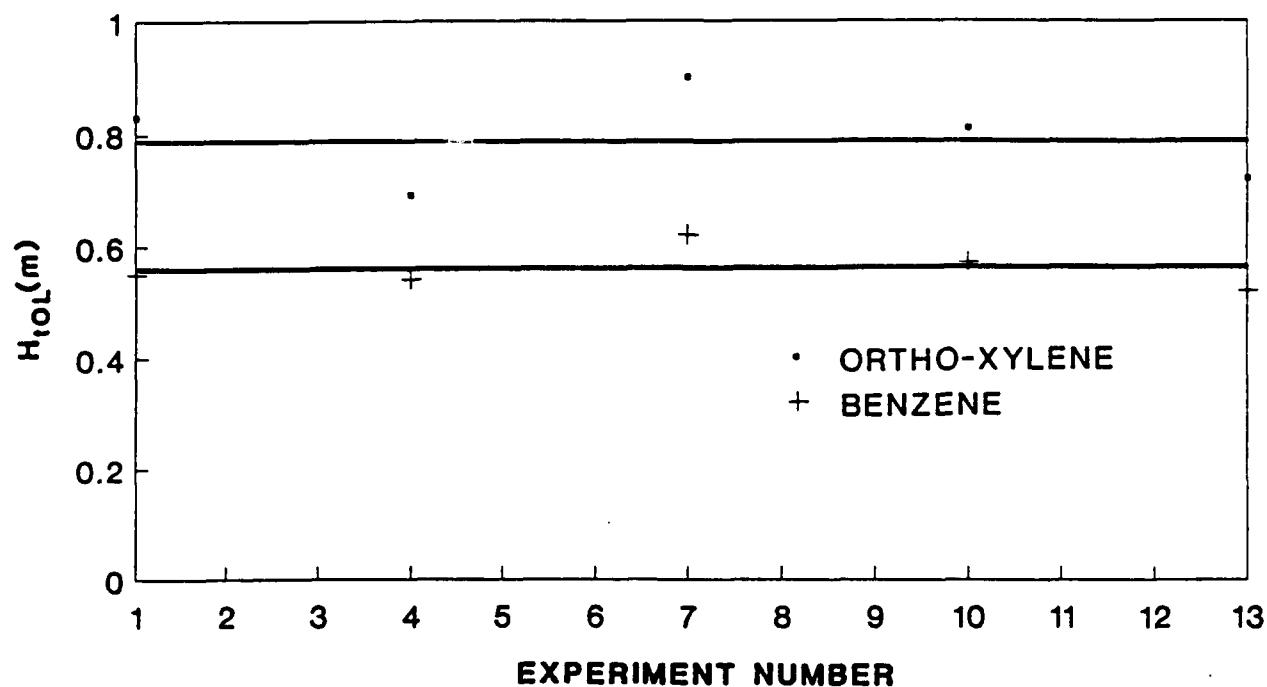


Figure 22. Comparison of Experimental Centerpoint  $H_{tOL}$  Values for Benzene and Ortho-Xylene vs. Run Number.

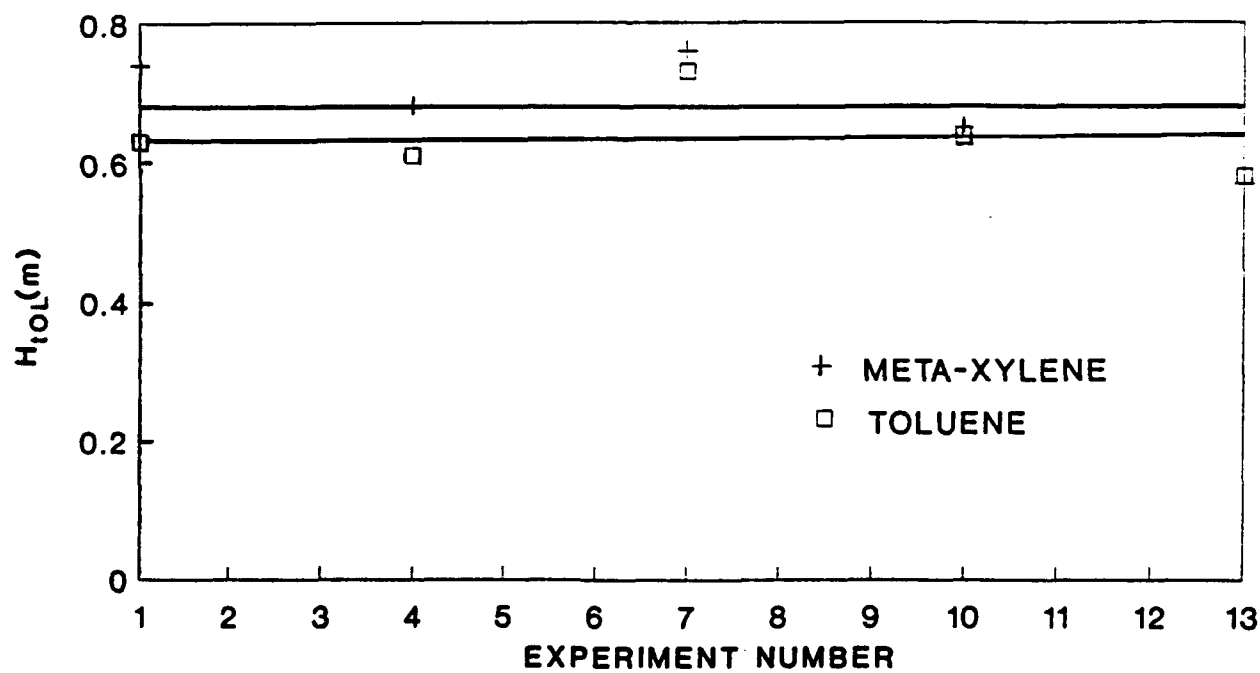


Figure 22. Comparison of Experimental Centerpoint  $H_{tOL}$  Values for Toluene and Meta-Xylene vs. Run Number. (Continued)

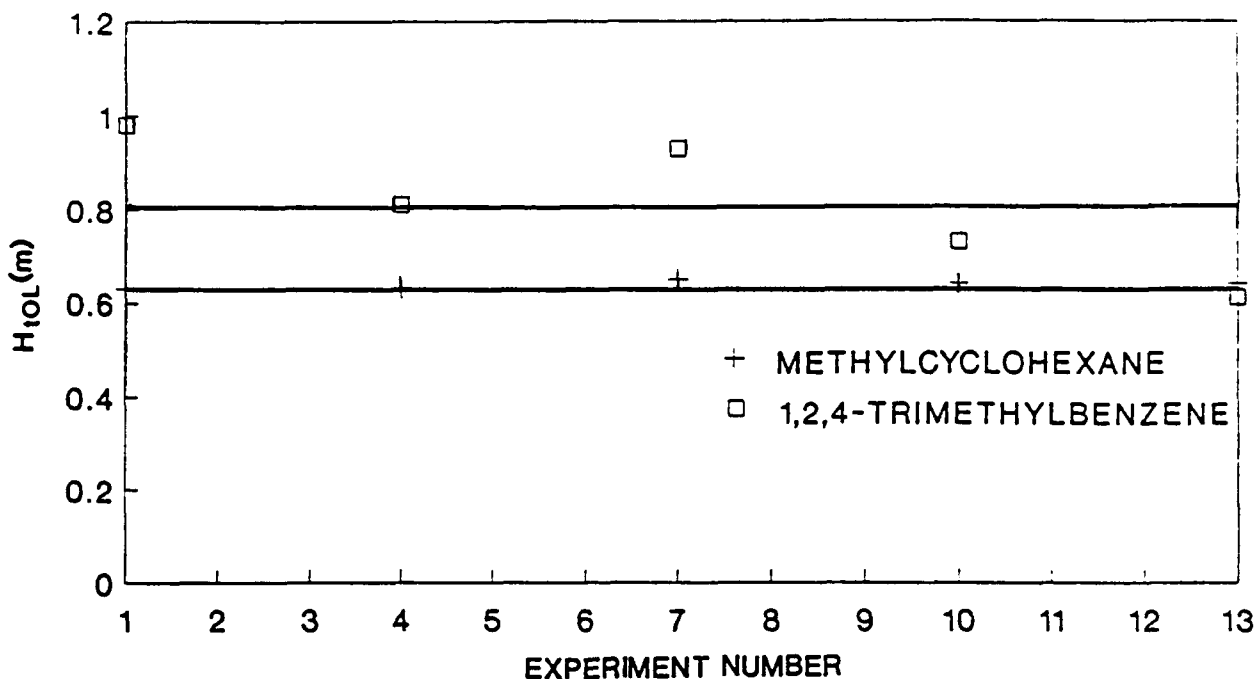


Figure 22. Comparison of Experimental Centerpoint  $H_{OL}$  Values for 1,2,4-Trimethylbenzene and Methylcyclohexane vs. Run Number. (Concluded)

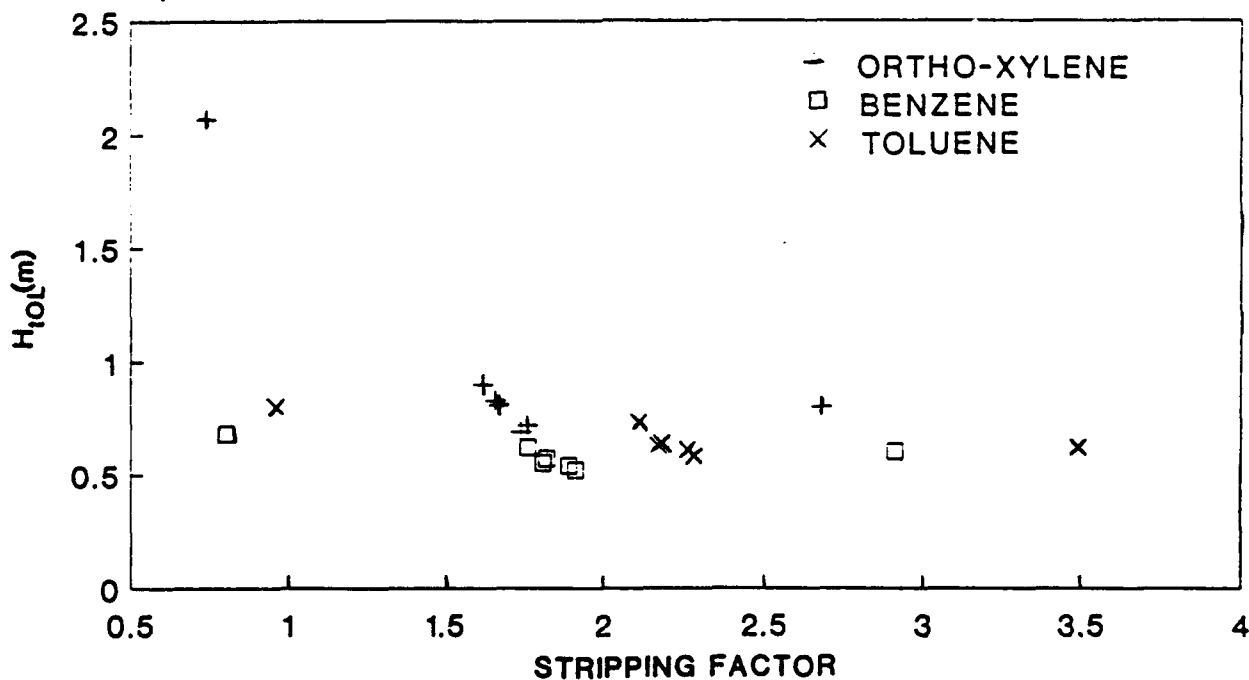


Figure 23. Comparison of Experimental  $H_{OL}$  Values for Ortho-Xylene, Benzene, and Toluene vs. Stripping Factor at a Liquid Rate of  $10.7 \text{ kg/m}^2\text{s}$  from Tests with Flexiring® Packing.



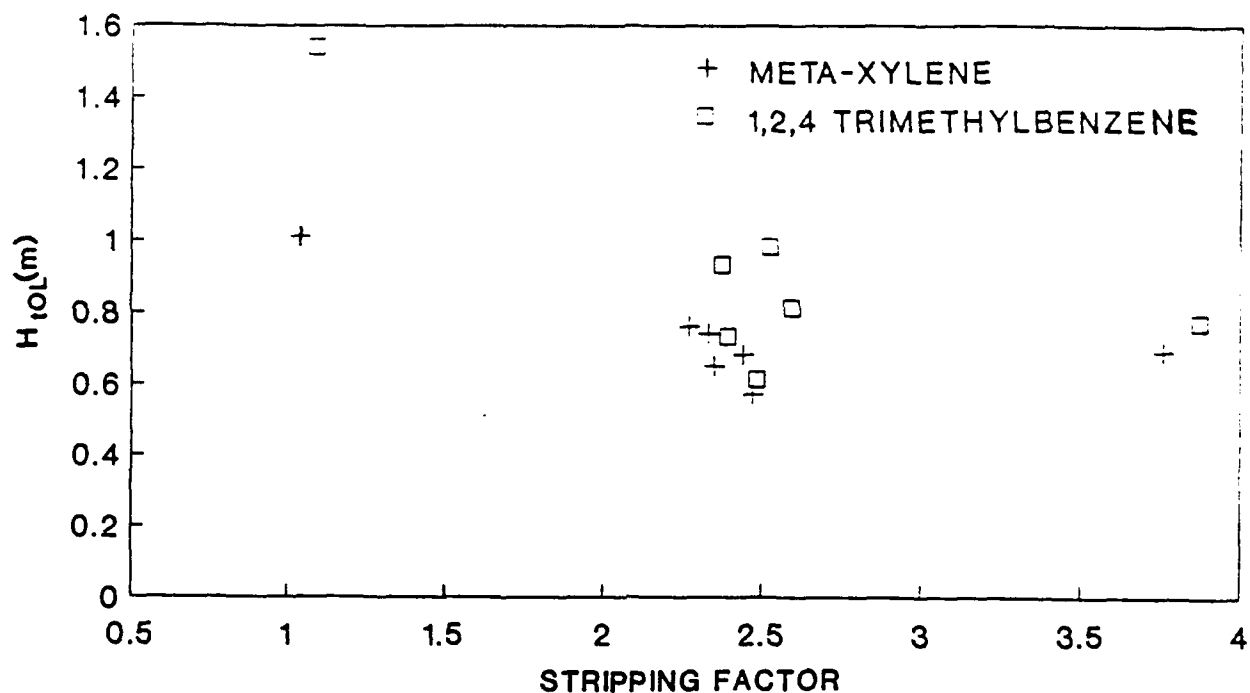


Figure 23. Comparison of Experimental  $H_{OL}$  Values for Meta-Xylene and 1,2,4-Trimethylbenzene vs. Stripping Factor at a Liquid Rate of  $10.7 \text{ kg/m}^2\text{s}$  from Tests with Flexiring® Packing. (Continued)

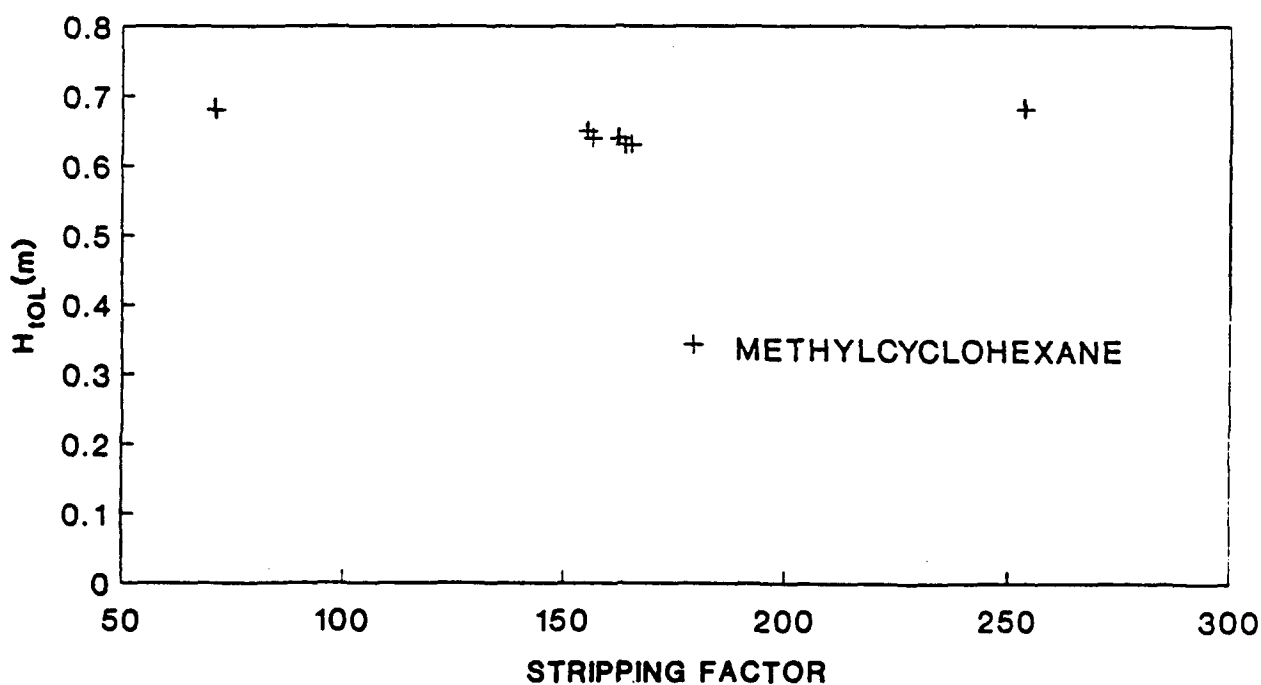


Figure 23. Comparison of Experimental  $H_{OL}$  Values for Methylcyclohexane vs. Stripping Factor at a Liquid Rate of  $10.7 \text{ kg/m}^2\text{s}$  from Tests with Flexiring® Packing. (Concluded)

TABLE 13. EXPERIMENTAL  $H_{OL}$  VALUES FOR SYNTHESIZED SOLUTION OF ORTHO-XYLENE AND META-XYLENE IN TAPWATER

RUN #	LIQ. RATE kg/m <sup>2</sup> -s	GAS RATE SCFM	ORTHO-XYLENE		META-XYLENE	
			STRIPPING FACTOR	$H_{OL}$ (m)	STRIPPING FACTOR	$H_{OL}$ (m)
1	11.0	0.141	2.37	0.53	3.36	0.51
3	16.7	0.210	2.32	0.58	3.30	0.56
5	5.25	0.068	2.40	0.40	3.42	0.38
6	10.9	0.060	0.93	0.67	1.31	0.61
9	11.1	0.221	3.39	0.66	4.80	0.60
10	10.7	0.134	2.11	0.597	3.00	0.55

Note: Flexiring® packing. Packed Height = 3.05 meters and tower cross-sectional area = 0.078 m<sup>2</sup>.

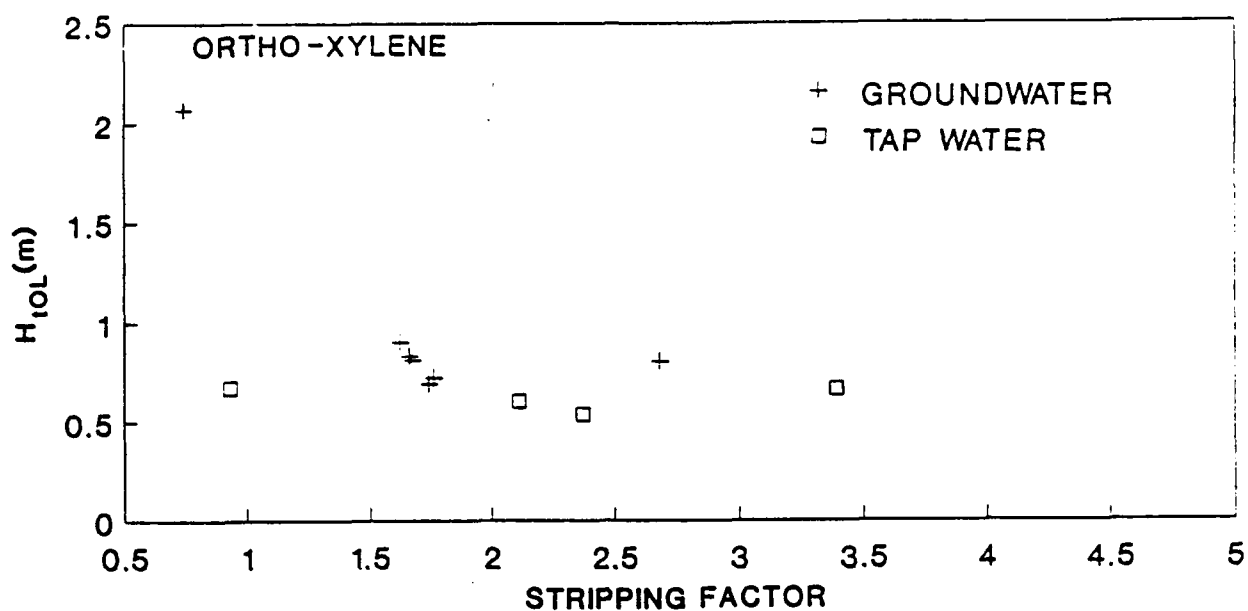


Figure 24. Presentation of  $H_{10L}$  Values vs. Stripping Factor for Ortho-Xylene from Tests with Groundwater and Tests with Tapwater.

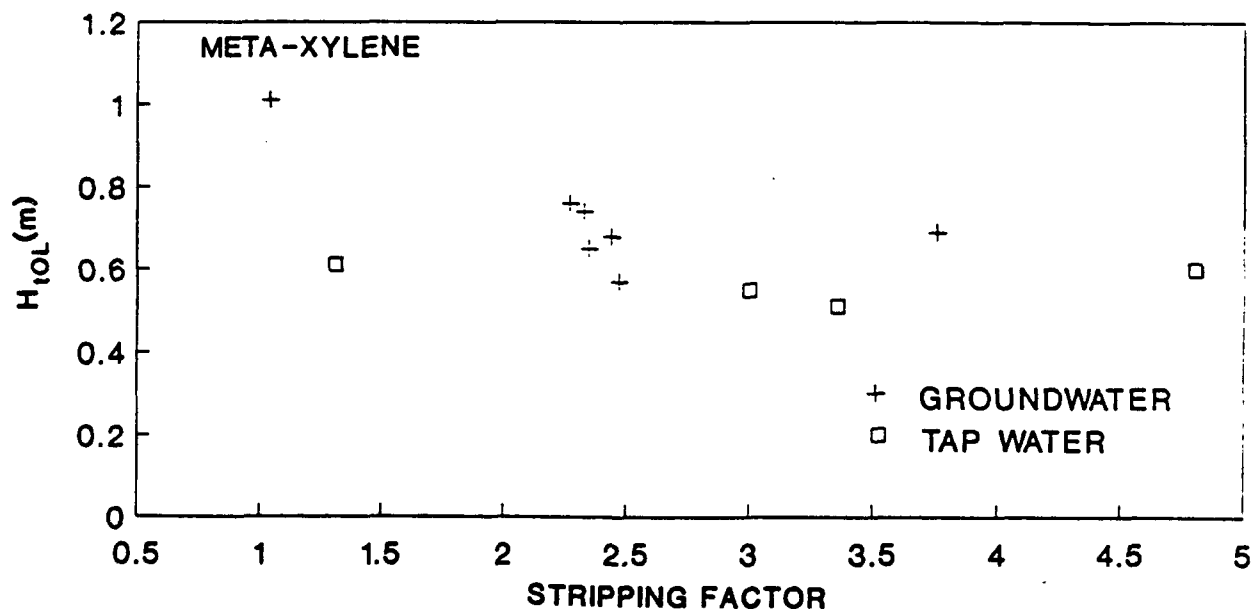


Figure 24. Presentation of  $H_{10L}$  Values vs. Stripping Factor for Meta-Xylene from Tests with Groundwater and Tests with Tapwater. (Concluded)

experimental  $H_{OL}$  values to the values predicted utilizing the Onda equation (Reference 15). This would help account for the temperature difference between the groundwater and the tapwater tests. The normalized  $H_{OL}$  values tests with tapwater were also found to be within a 95 percent confidence interval of the normalized  $H_{OL}$  values from the tests with groundwater, indicating that the data from tests with groundwater could be used for general design purposes.

The  $H_{OL}$  values for the Flexirings® were compared to those predicted using two established correlations, the Bolles and Fair model (Reference 12) and the Onda model (Reference 15). The residuals from these comparisons is shown in Figure 25. The predictions utilizing the Onda model agreed well with the observed values, but the predictions based on the Bolles and Fair model tended to be high.

As a comparison with previous studies, Stallings and Rogers (Reference 26) found that the Onda equation, in general, provided mass transfer coefficients that agreed reasonably well with the experimental data for benzene stripping using 25-mm plastic Flexirings®. They also observed that the  $H_{OL}$  for benzene generally increased with increasing liquid rate and decreased with increasing gas-to-liquid ratio. Gossett et al. (Reference 36) found that the Onda equation predicted their stripping data well for removal of trichloroethylene from water using 16-, 25-, and 50-mm plastic Flexirings®.

## **2. Koch/Sulzer Type BX Packing**

Hydraulic tests with Koch/Sulzer packing revealed two problems that complicated testing and analysis. At the high liquid rates originally planned for this packing, the liquid flow observed at the bottom of the packing was unequally distributed when viewed through the sight glass below the packed section of the tower; the liquid tended to channel through the center of the packing. This type of packing is designed for fairly low liquid rates. Lowering the maximum liquid rate from  $28.6 \text{ kg/m}^2\text{-s}$  to  $16.7 \text{ kg/m}^2\text{-s}$  provided acceptable distribution. The second problem involved a change in hydraulic characteristics over time. Figure 26 shows initial hydraulic tests with tapwater. After running tests with groundwater the pressure drops actually decreased slightly. This effect is seen by comparing Figures 26 and 27. After the tests, the packing was closely examined. Initially the plastic gauze had some fibers which were sticking out.

These fibers gave a "hairy" quality to the packing that could have an increased tendency to hold up the liquid on the packing. After running experiments with groundwater, iron deposits apparently produced a smoother surface. This would tend to decrease liquid hold-up and, consequently, decrease the pressure drop. The packing was not tested long enough to see if the pressure drop would increase due to iron accumulation.

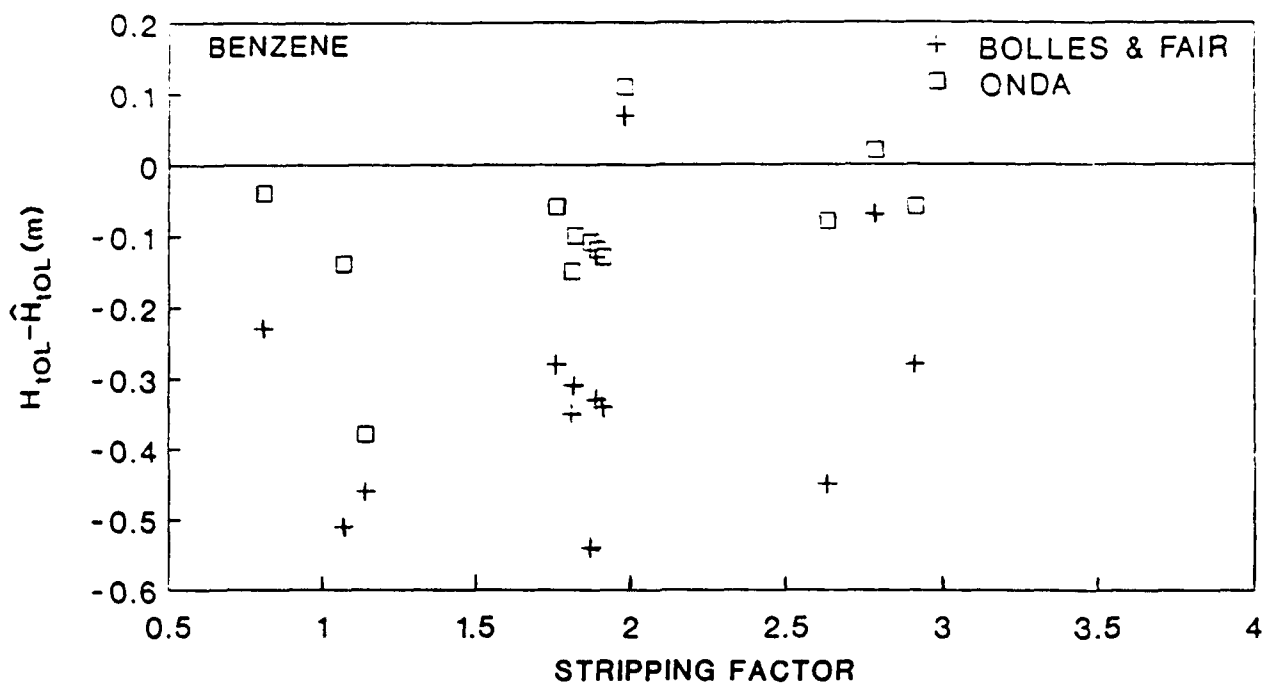


Figure 25. Residuals from the Comparison of Observed and Predicted  $H_{OL}$  vs. Stripping Factor for Benzene.

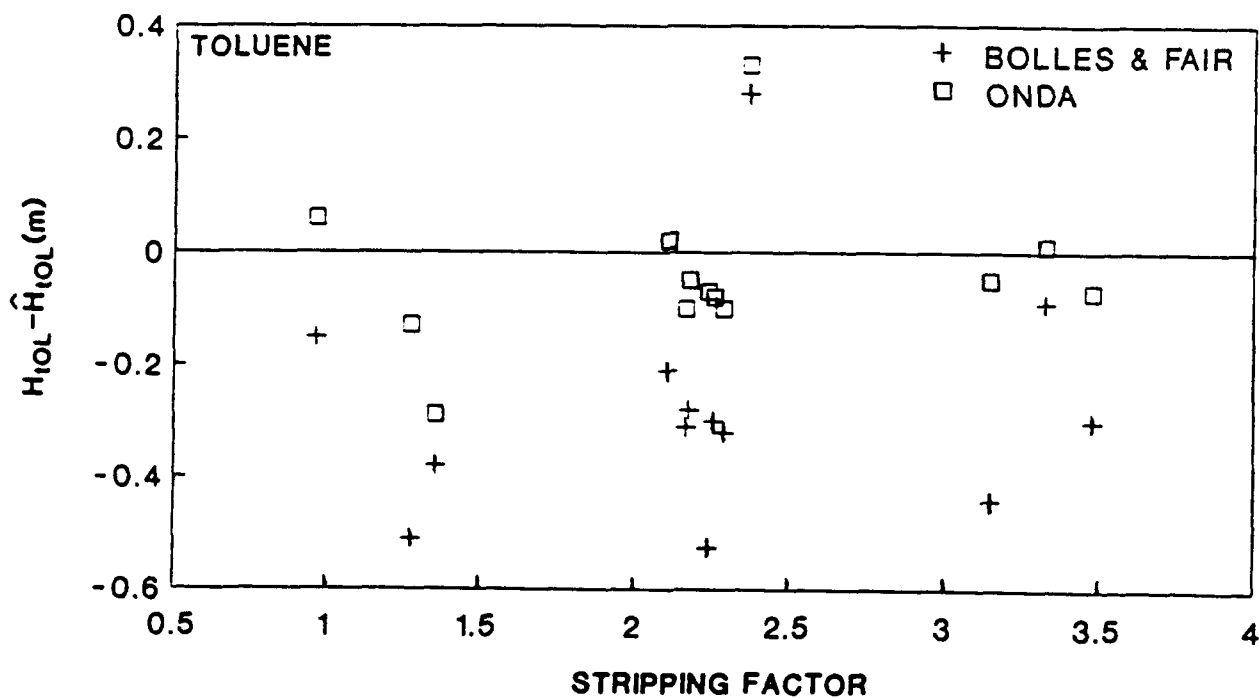


Figure 25. Residuals from the Comparison of Observed and Predicted  $H_{OL}$  vs. Stripping Factor for Toluene. (Continued)

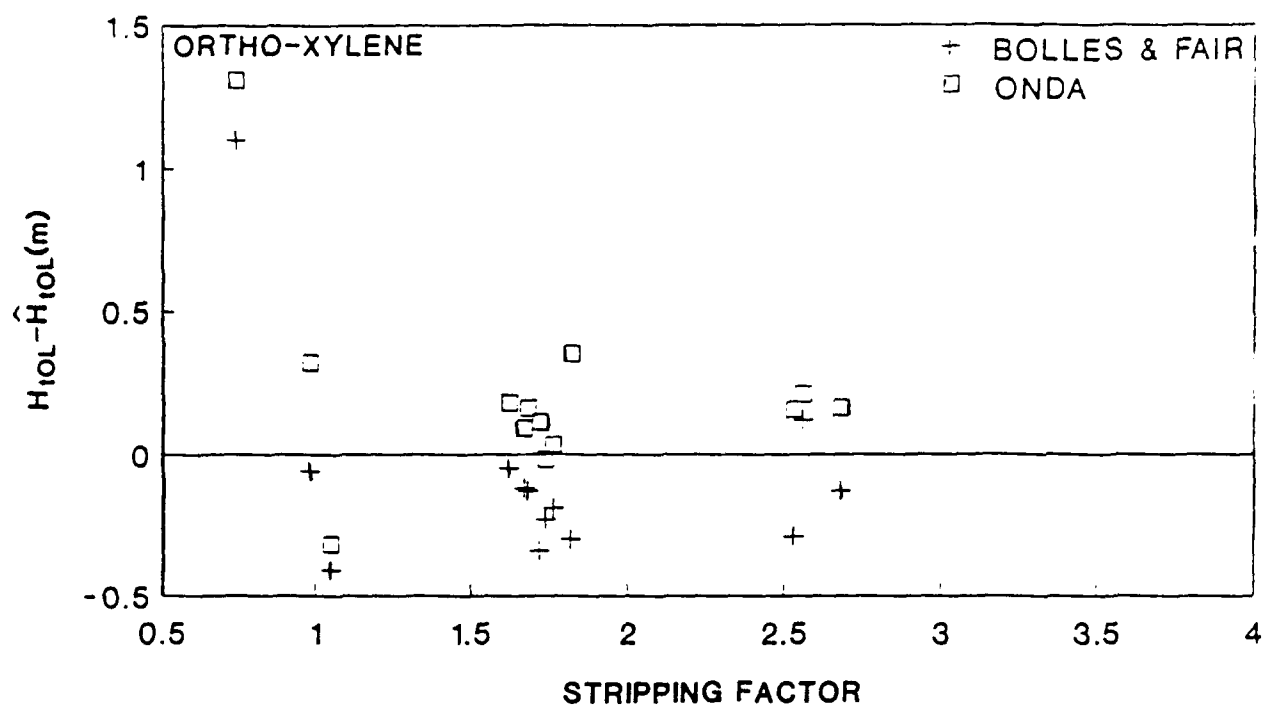


Figure 25. Residuals from the Comparison of Observed and Predicted  $H_{10L}$  vs. Stripping Factor for Ortho-Xylene. (Continued)

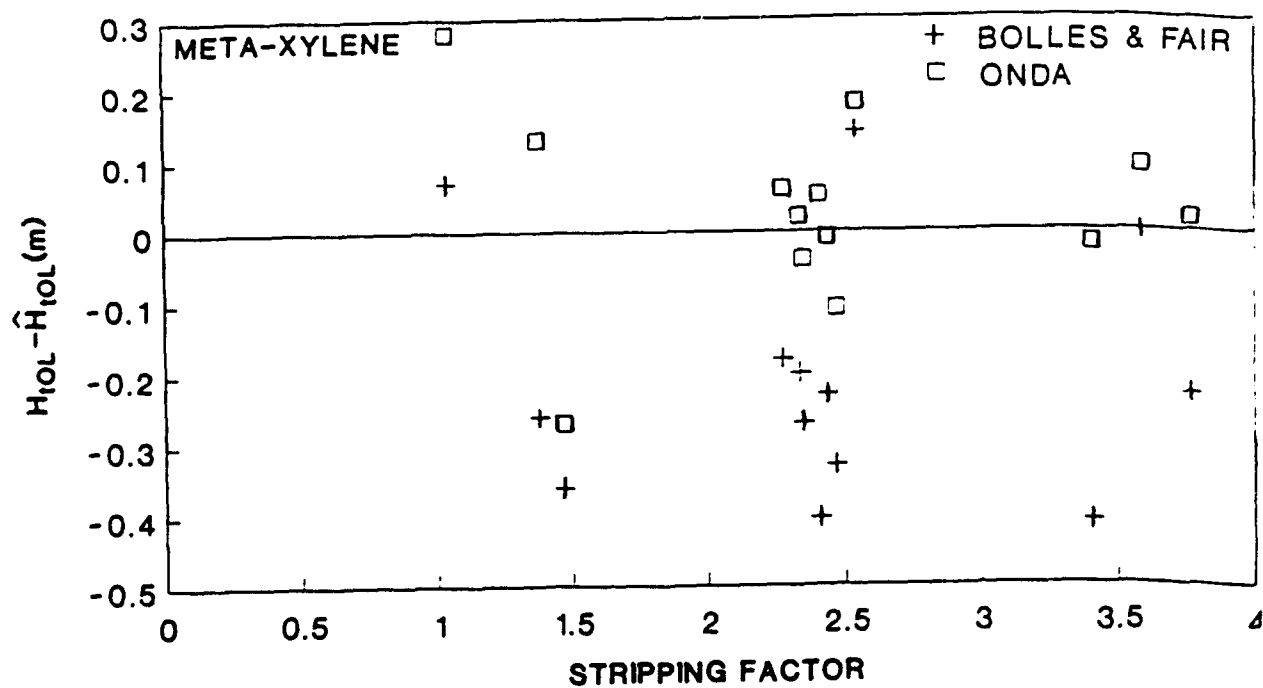


Figure 25. Residuals from the Comparison of Observed and Predicted  $H_{10L}$  vs. Stripping Factor for Meta-Xylene. (Continued)

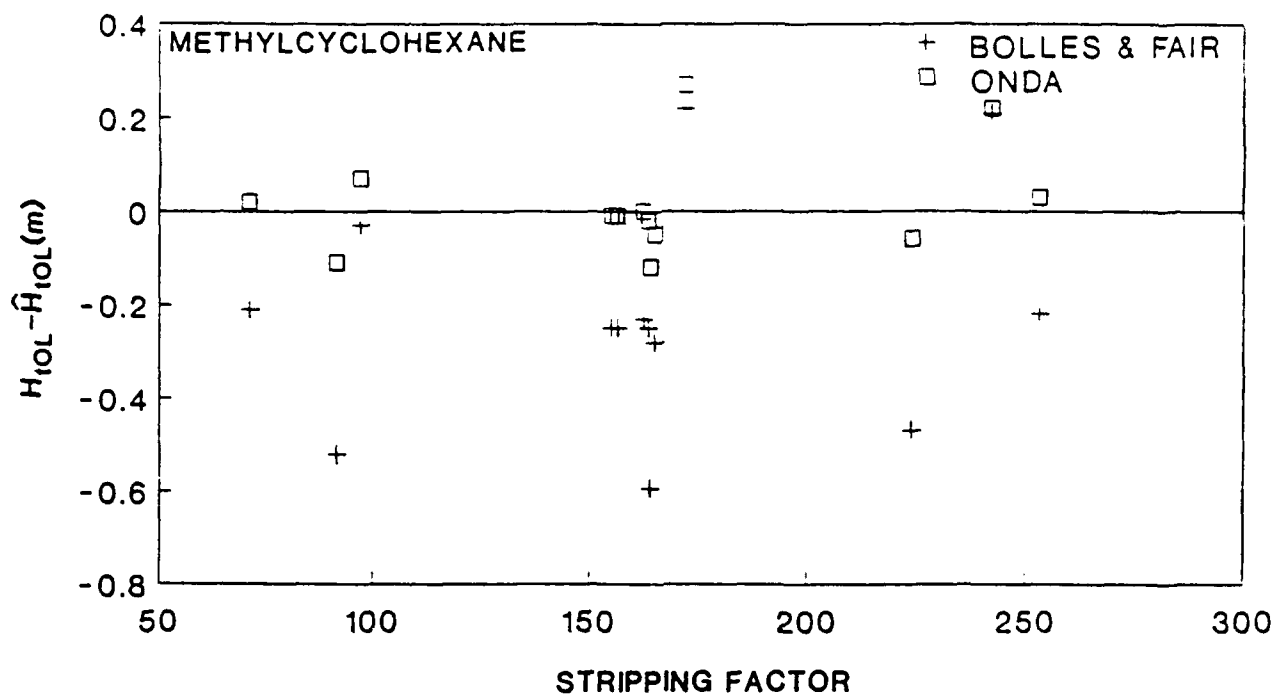


Figure 25. Residuals from the Comparison of Observed and Predicted  $H_{OL}$  vs. Stripping Factor for Methylcyclohexane. (Continued)

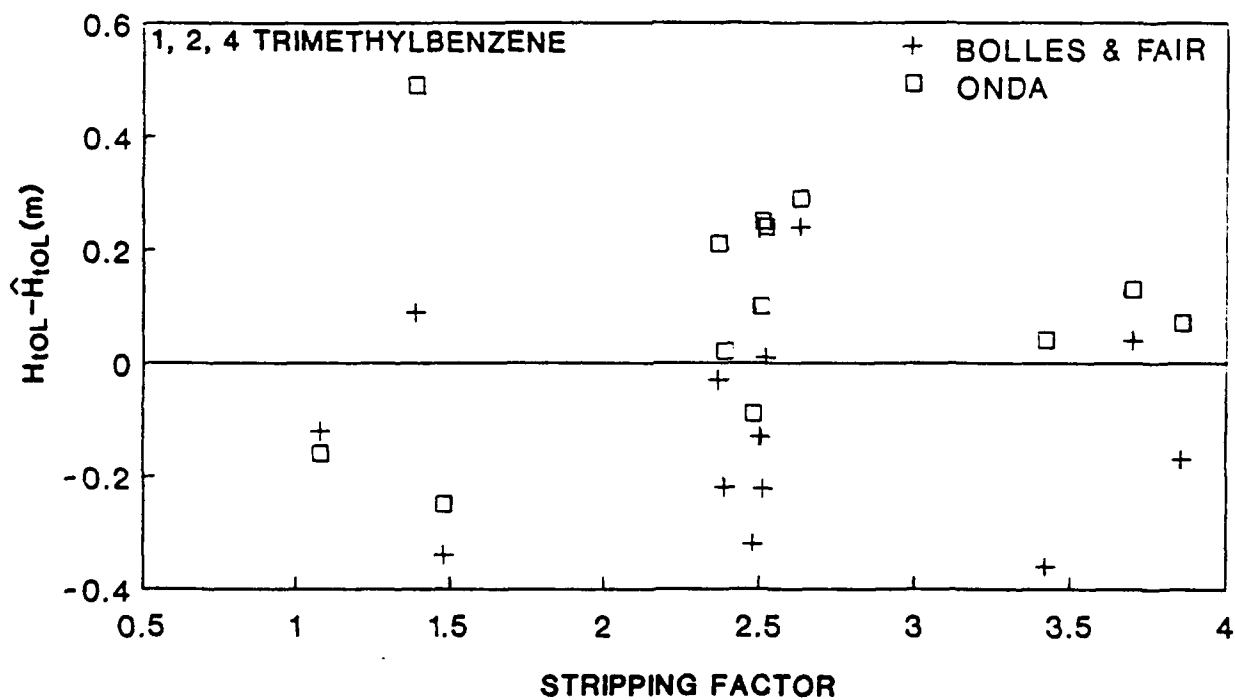


Figure 25. Residuals from the Comparison of Observed and Predicted  $H_{OL}$  vs. Stripping Factor for 1,2,4-Trimethylbenzene. (Concluded)

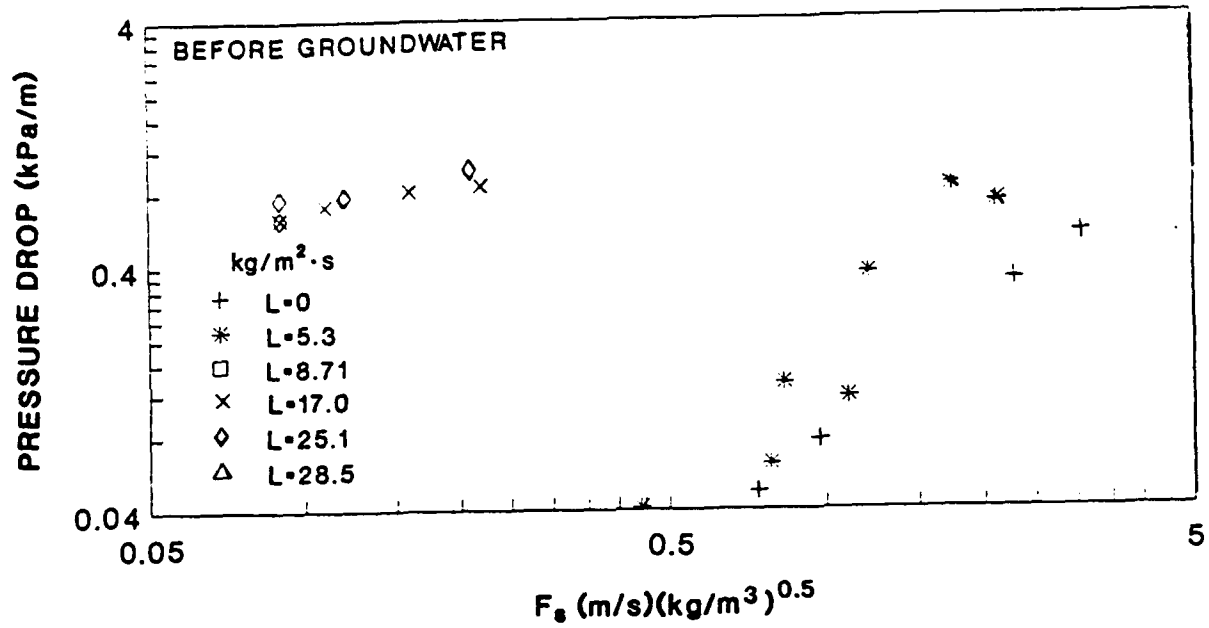


Figure 26. Hydraulic Tests on New Koch/Sulzer Type BX Plastic Packing with Tapwater.

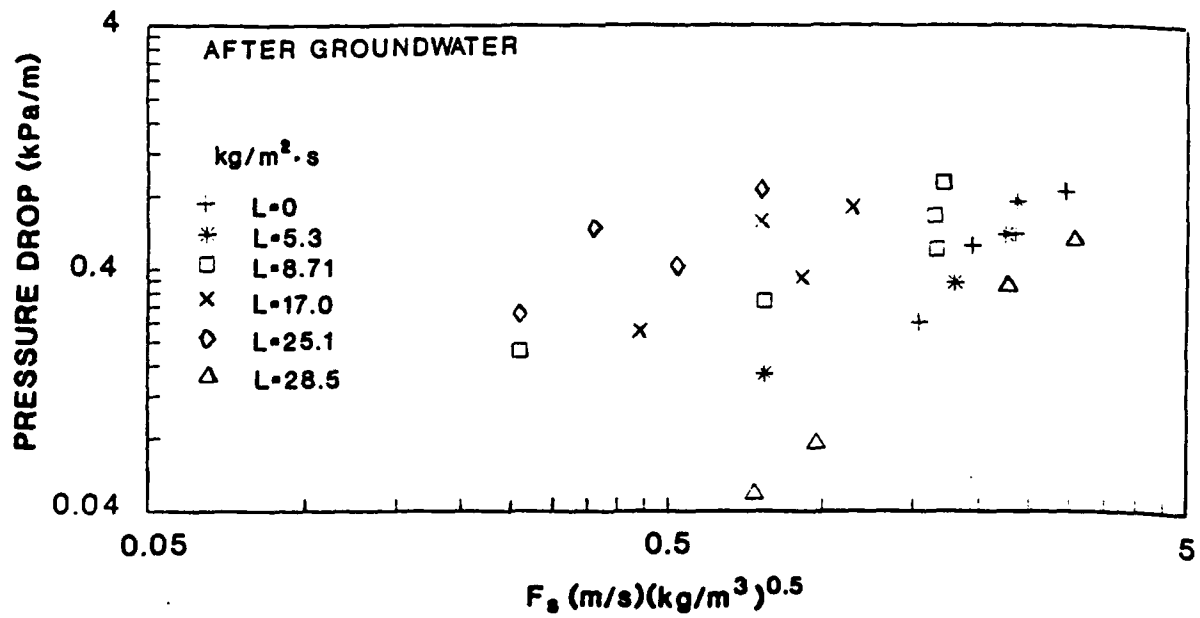


Figure 27. Hydraulic Tests on New Koch/Sulzer Type BX Plastic Packing after Groundwater had been used in the Tower.



The overall  $H_{iOL}$  values for the Koch/Sulzer Type BX Packing are shown in Table 14. The  $H_{iOL}$  values for the Koch/Sulzer packing were calculated by dividing the depth of packing,  $Z$ , by the  $N_{iOL}$ . The  $N_{iOL}$  was obtained by using Equation (17). Although the stripping factor had little effect on the  $H_{iOL}$ , the liquid rate had a strong effect. The stripping factor was not expected to have a large effect for two reasons; the plastic gauze material tends to stay fully wetted, and the liquid distribution is uniform. The effect of liquid rate is shown in Figure 28. The centerpoints were repeated during the experiments to test if the packing was degrading with time. The variation in centerpoints is shown in Figure 29. As with the Flexirings®, the change over the experimental series was not significant above the scatter in the data. Since the lowest  $H_{iOL}$  occurred at the lowest liquid rates, an additional series of experiments was conducted at very low liquid rates. The results from these tests are shown in Table 15, and the effect of liquid rate is shown in Figure 30.

The experimental design was set up to determine the effects of liquid rate and stripping factor according to the empirical model  $H_{iOL} = a_1 L_v + a_2 S + a_3 L_v S + a_4 L_v^2 + a_5 S^2$ . Statistical analysis of the data based on this model determined the relative effects and significance of the variables. This analysis showed only an effect of liquid rate at a 90 percent confidence level for all compounds examined. An empirical model for the  $H_{iOL}$  based on a regression of the packing is as follows:

$$H_{iOL} = 475 * L_v + 0.03 \quad (57)$$

where  $L_v$  is in  $m^3/\text{second}$ .

Most of the uncertainty in estimation of  $H_{iOL}$  for the Koch/Sulzer packing was in the  $H_L$  estimation. By utilizing a correlation of  $H_G$  by Bomio (Reference 19), the experimental  $H_L$  was extracted from the experimental  $H_{iOL}$  values. Dimensional analysis was then utilized to develop a general correlation for  $H_L$  (Reference 38). The gas-liquid interfacial area was assumed to be that of the dry area of the packing. It may be noted that the  $H_G/S$  term was negligible for the Koch/Sulzer Packing. Application of the Buckingham Pi Method yielded the form of the model:

$$Sh = C_1 Re_L^{c_2} Sc_L^{c_3} \quad (58)$$

where

$$Sh = \frac{k_L d_m}{D_L} \quad (59)$$

or

TABLE 14. EXPERIMENTAL  $H_{OL}$  FOR KOCH/SULZER PACKING

Run #	Liquid Rate $kg/m^2-s$	Gas Rate $kg/m^2-s$	Ortho-Xylene		Benzene		Methylcyclohexane		Toluene	
			Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)
1	11.1	0.139	1.67	0.69	1.87	0.48	158.97	0.49	2.17	0.56
2	14.9	0.104	0.93	0.87	1.05	0.50	89.12	0.45	1.21	0.60
3	16.4	0.216	1.73	1.21	1.95	0.72	167.80	0.46	2.26	0.63
4	10.6	0.134	1.65	0.53	1.86	0.38	161.21	0.54	2.16	0.40
5	5.25	0.072	1.77	0.36	1.99	0.31	175.04	0.52	2.31	0.27
6	10.9	0.053	0.63	-----	0.71	----	62.30	0.55	0.82	----
7	11.0	0.139	1.69	0.48	1.90	0.45	161.31	0.49	2.20	0.41
8	6.71	0.124	2.46	0.44	2.77	0.39	234.62	0.57	3.20	0.38
9	10.8	0.217	2.67	0.60	3.00	0.47	254.78	0.54	3.48	0.42
10	10.7	0.137	1.70	0.55	1.91	0.42	163.51	0.56	2.22	0.37
11	14.5	0.273	2.43	1.24	2.73	0.74	240.44	0.47	3.17	0.77
12	6.71	0.053	1.01	0.25	1.13	0.16	99.83	0.55	1.31	0.21
13	10.7	0.137	1.64	0.52	1.85	0.36	162.73	0.53	2.14	0.38

Note: Packing height = 1.35 meters and tower cross-sectional area = 0.078  $m^2$ .

TABLE 14. EXPERIMENTAL  $H_{OL}$  FOR KOCH/SULZER PACKING (CONCLUDED)

Run #	Liquid Rate $\text{kg/m}^2\text{-s}$	Gas Rate $\text{kg/m}^2\text{-s}$	Meta-Xylene		1,2,4-Trimethylbenzene	
			Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)
1	11.1	0.139	2.34	0.46	2.42	0.43
2	14.9	0.174	1.31	0.52	1.36	0.45
3	16.4	0.216	2.43	0.75	2.56	0.66
4	10.6	0.134	2.32	0.38	2.46	0.38
5	5.25	0.072	2.48	0.28	2.67	0.27
6	10.9	0.053	0.88	-----	0.95	0.11
7	11.0	0.139	2.37	0.36	2.46	0.36
8	6.71	0.124	3.45	0.35	3.58	0.35
9	10.8	0.217	3.75	0.44	3.88	0.44
10	10.7	0.137	2.39	0.42	2.49	0.41
11	14.5	0.273	3.40	0.90	3.67	0.80
12	6.71	0.053	1.41	0.25	1.52	0.26
13	10.7	0.137	2.30	0.42	2.48	0.42

Note: Packing height = 1.35 meters and tower cross-sectional area = 0.078  $\text{m}^2$ .

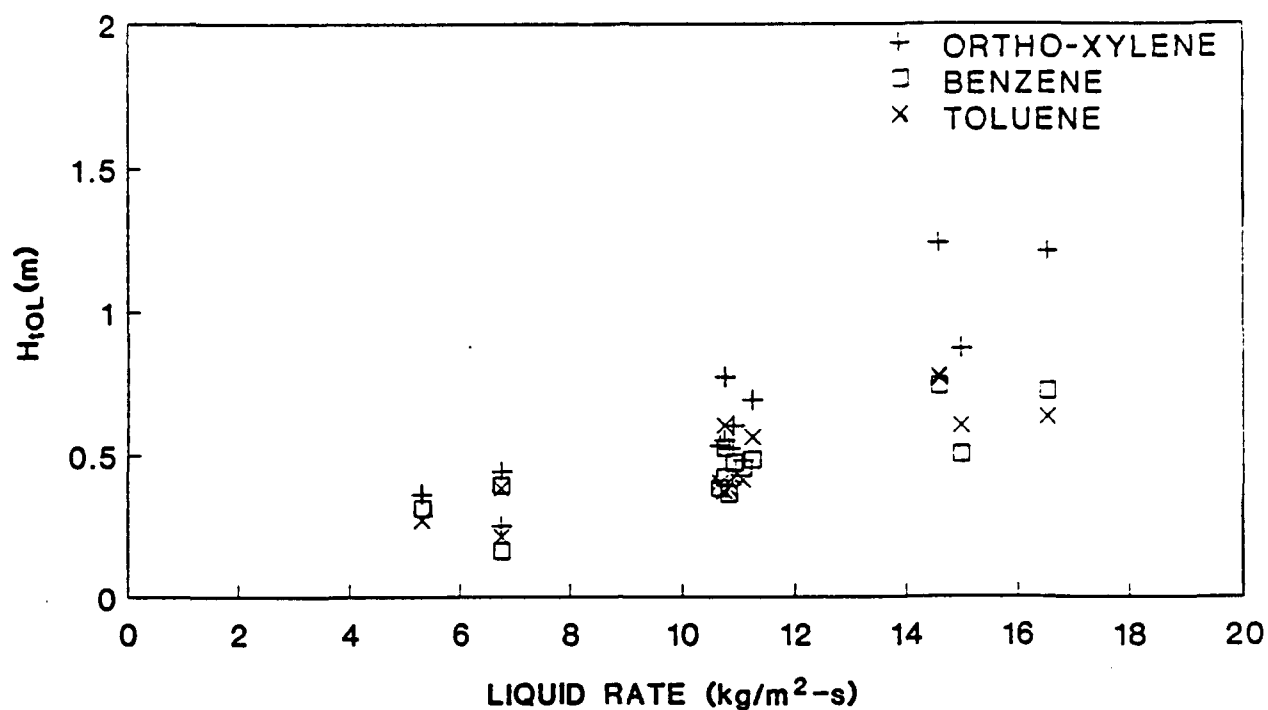


Figure 28. Effect of Liquid Rate on the Experimental  $H_{OL}$  for Ortho-Xylene, Benzene, and Toluene using Koch/Sulzer Type BX Plastic Packing.

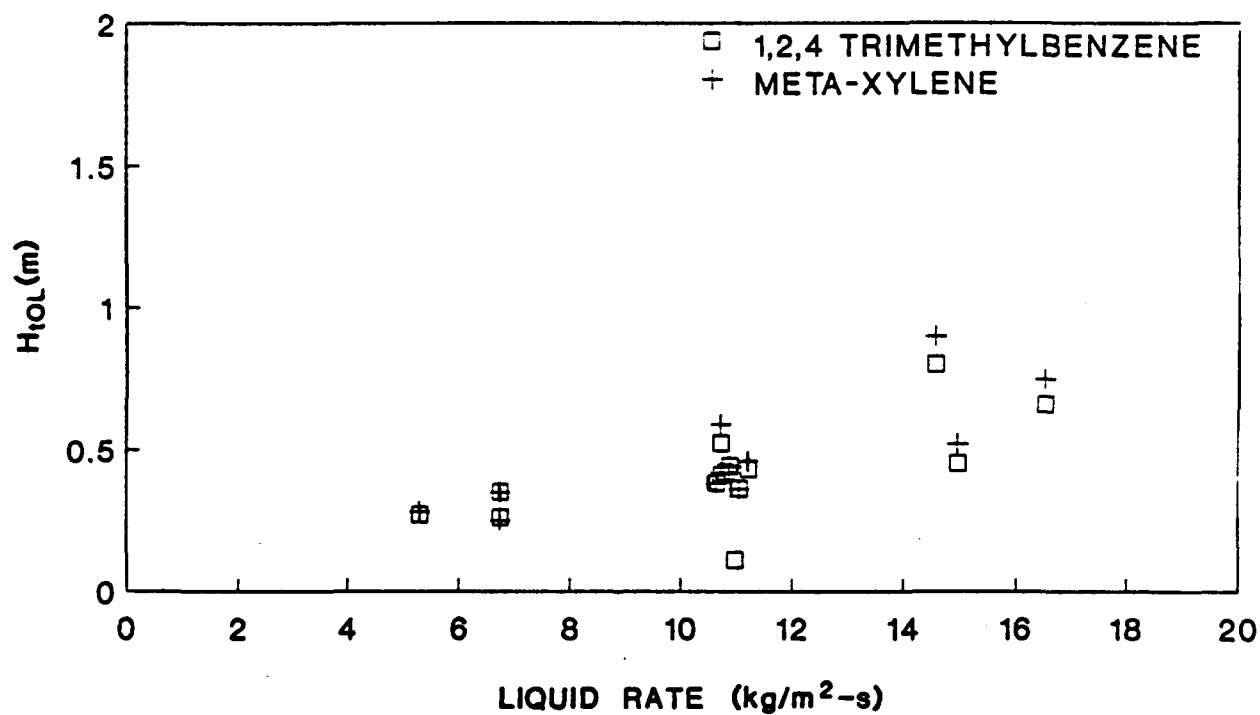


Figure 28. Effect of Liquid Rate on the Experimental  $H_{OL}$  for 1,2,4-Trimethylbenzene and Meta-Xylene using Koch/Sulzer Type BX Plastic Packing. (Continued)

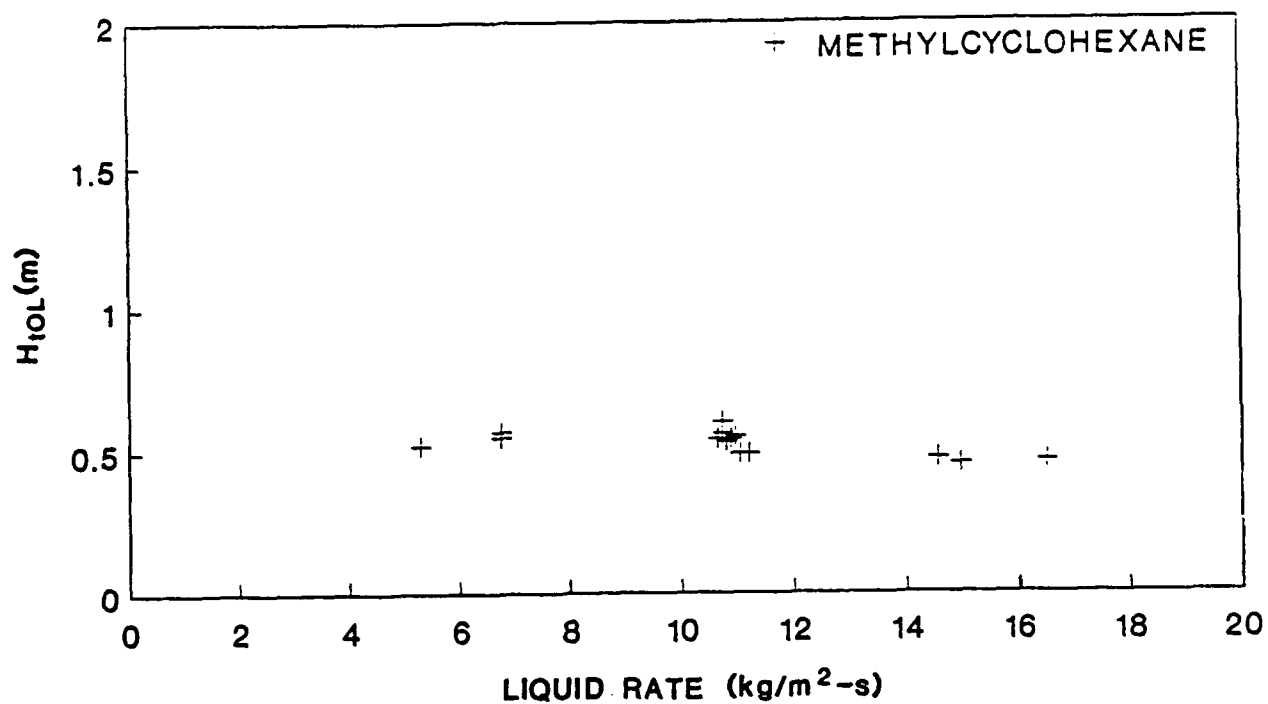


Figure 28. Effect of Liquid Rate on the Experimental  $H_{OL}$  for Methylcyclohexane using Koch/Sulzer Type BX Plastic Packing. (Concluded)

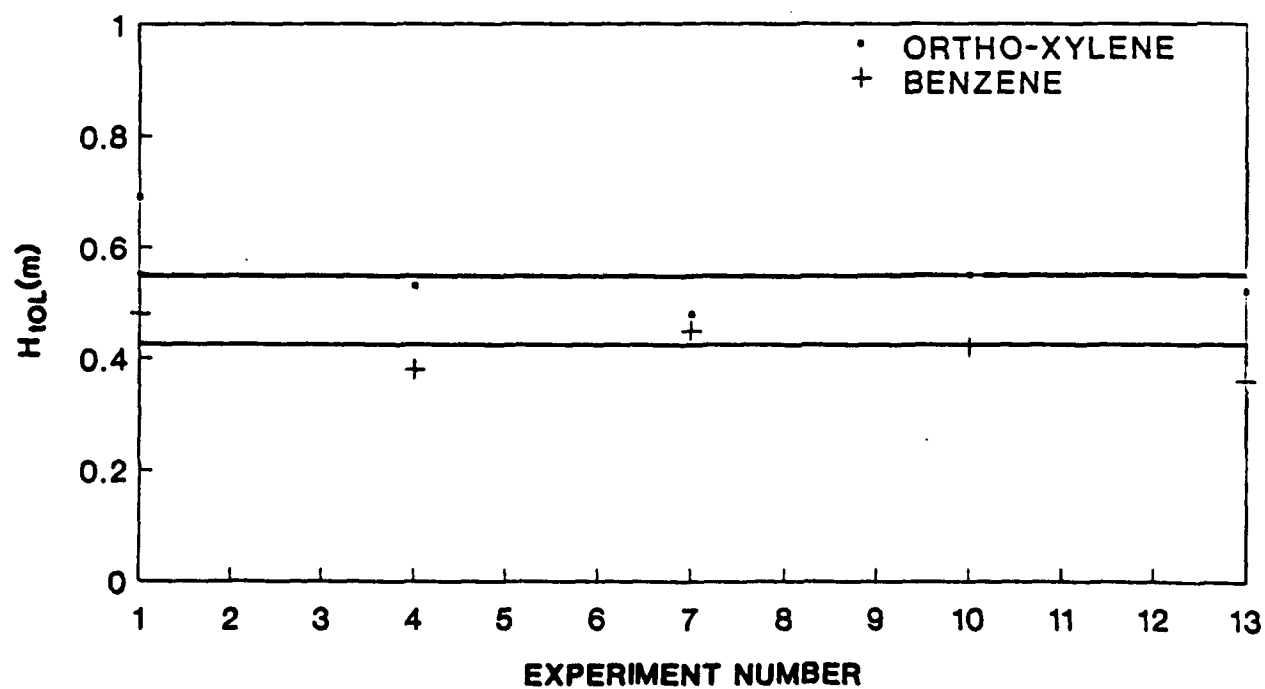


Figure 29. Variation in Experimental Centerpoint  $H_{OL}$  Values for Ortho-Xylene and Benzene.

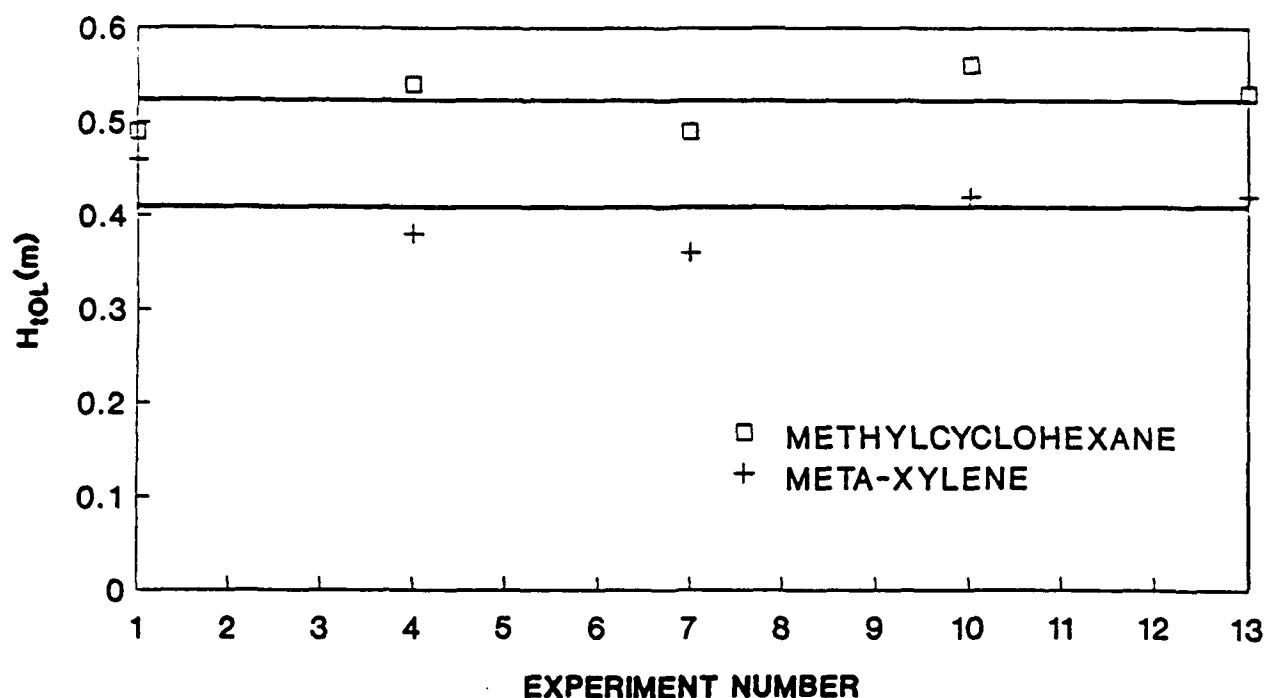


Figure 29. Variation in Experimental Centerpoint  $H_{10L}$  Values for Methylcyclohexane and Meta-Xylene. (Continued)

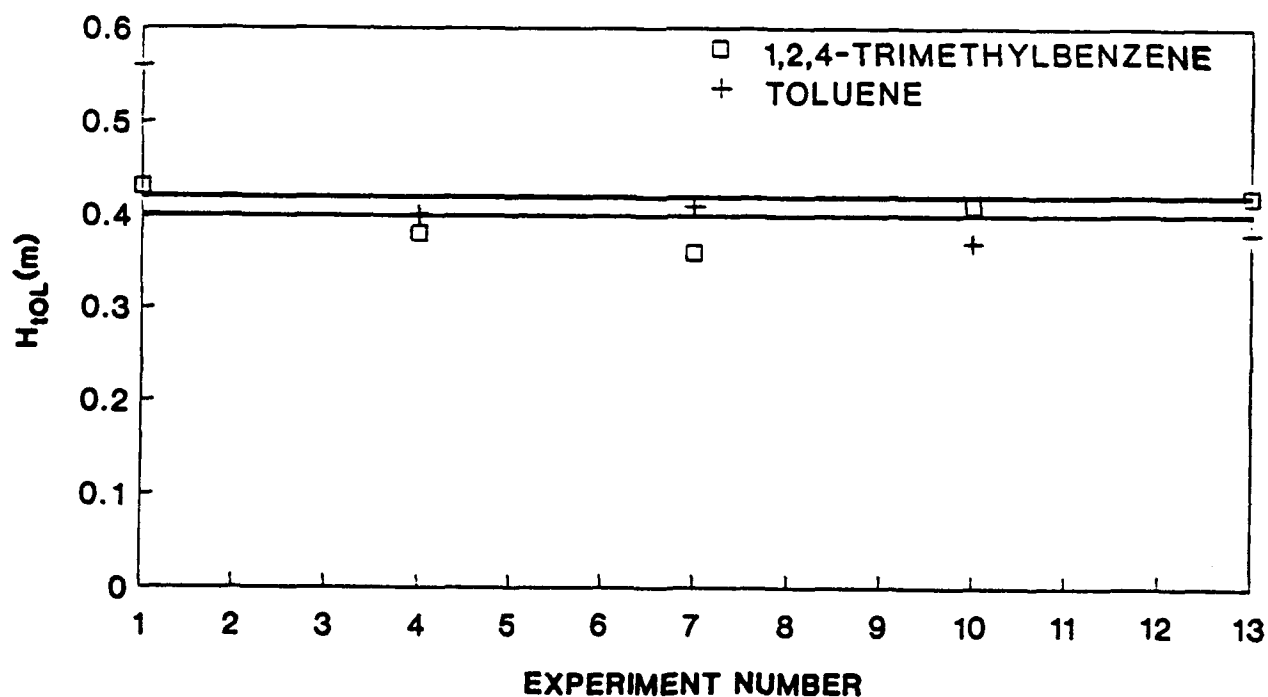


Figure 29. Variation in Experimental Centerpoint  $H_{10L}$  Values for 1,2,4-Trimethylbenzene and Toluene. (Concluded)

TABLE 15. HEIGHT OF A TRANSFER UNIT FOR KOCH/SULZER TYPE BX PLASTIC PACKING AT LOW LIQUID LOADINGS

Run #	Liquid Rate kg/m <sup>2</sup> -s	Gas Rate kg/m <sup>2</sup> -s	Ortho-Xylene		Pentane		Benzene		Methylcyclohexane	
			Stripping Factor	H <sub>OL</sub> (m)	Stripping Factor	H <sub>OL</sub> (m)	Stripping Factor	H <sub>OL</sub> (m)	Stripping Factor	H <sub>OL</sub> (m)
1	3.23	0.0521	2.17	0.45	655.40	0.36	2.44	0.43	204.81	0.38
2	1.54	0.0393	3.44	0.30	1038.37	0.27	3.87	0.36	324.49	0.30
3	1.54	0.0255	2.14	0.28	678.64	0.29	2.41	0.28	212.07	0.29
4	3.39	0.0519	2.03	0.43	622.15	0.40	2.28	0.44	194.42	0.41
5	3.39	0.0980	3.75	0.48	1177.03	0.39	4.21	0.44	367.82	0.41
6	5.25	0.118	2.91	0.65	912.33	0.45	3.27	0.67	285.10	0.50
7	3.39	0.0521	1.96	0.42	627.63	0.38	2.20	0.45	196.13	0.42
8	3.39	0.0231	0.87	0.18	278.11	0.37	0.98	0.21	86.91	0.40
9	1.54	0.0125	1.07	0.05	330.71	0.26	1.20	0.12	103.35	0.24
10	3.39	0.0521	2.09	0.35	623.55	0.39	2.35	0.38	194.86	0.44
11	5.25	0.0336	0.877	0.22	259.42	0.51	0.99	0.25	81.07	0.60
12	5.25	0.0926	2.28	0.65	719.40	0.53	2.56	0.58	224.82	0.60
13	3.39	0.0516	2.04	0.32	618.61	0.40	2.30	0.32	193.32	0.46

Note: Packing height = 1.35 meters and tower cross-sectional area = 0.078 m<sup>2</sup>.

TABLE 15. HEIGHT OF A TRANSFER UNIT FOR KOCH/SULZER TYPE BX PLASTIC PACKING AT LOW LIQUID LOADINGS (CONCLUDED)

Run #	Liquid Rate kg/m <sup>2</sup> -s	Gas Rate kg/m <sup>2</sup> -s	Toluene		Meta-Xylene		1,2,4-Trimethylbenzene	
			Stripping Factor	H <sub>OL</sub> (m)	Stripping Factor	H <sub>OL</sub> (m)	Stripping Factor	H <sub>OL</sub> (m)
1	3.23	0.0521	2.83	0.42	3.05	0.44	3.12	0.50
2	1.54	0.0393	4.48	0.29	4.83	0.30	4.95	0.31
3	1.54	0.0255	2.79	0.26	3.00	0.25	3.23	0.25
4	3.39	0.0519	2.65	0.36	2.85	0.39	2.97	0.40
5	3.39	0.0980	4.88	0.38	5.25	0.42	5.61	0.43
6	5.25	0.118	3.80	0.53	4.08	0.55	4.35	0.54
7	3.39	0.0521	2.56	0.36	2.74	0.37	2.99	0.36
8	3.39	0.0231	1.14	0.19	1.22	0.22	1.33	0.23
9	1.54	0.0125	1.39	0.13	1.50	0.11	1.58	0.10
10	3.39	0.0521	2.72	0.36	2.94	0.31	2.97	0.29
11	5.25	0.0336	1.14	0.29	1.23	0.25	1.24	0.22
12	5.25	0.0926	2.97	0.53	3.19	0.52	3.43	0.51
13	3.39	0.0516	2.66	0.32	2.87	0.27	2.95	0.26

Note: Packing height = 1.35 meters and tower cross-sectional area = 0.078 m<sup>2</sup>.



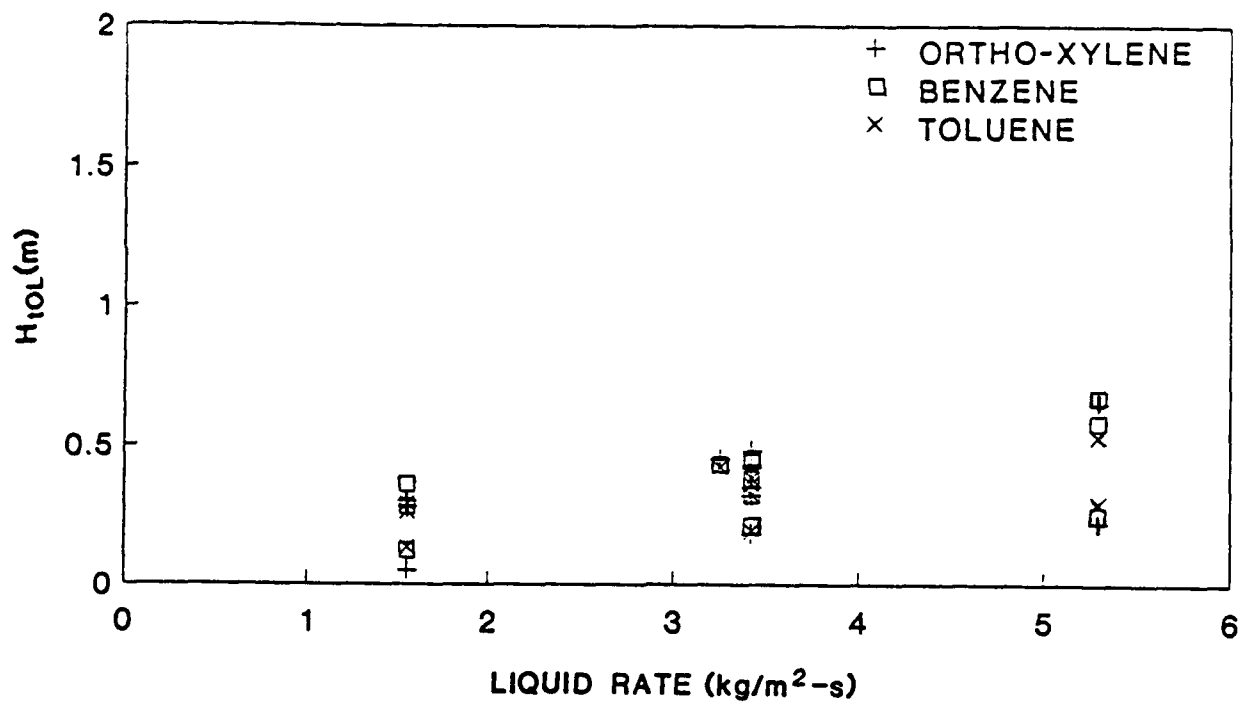


Figure 30. Effect of Liquid Rate on the Experimental  $H_{OL}$  for Ortho-Xylene, Benzene, and Toluene using Koch/Sulzer Type BX Plastic Packing at Low Liquid Rates.

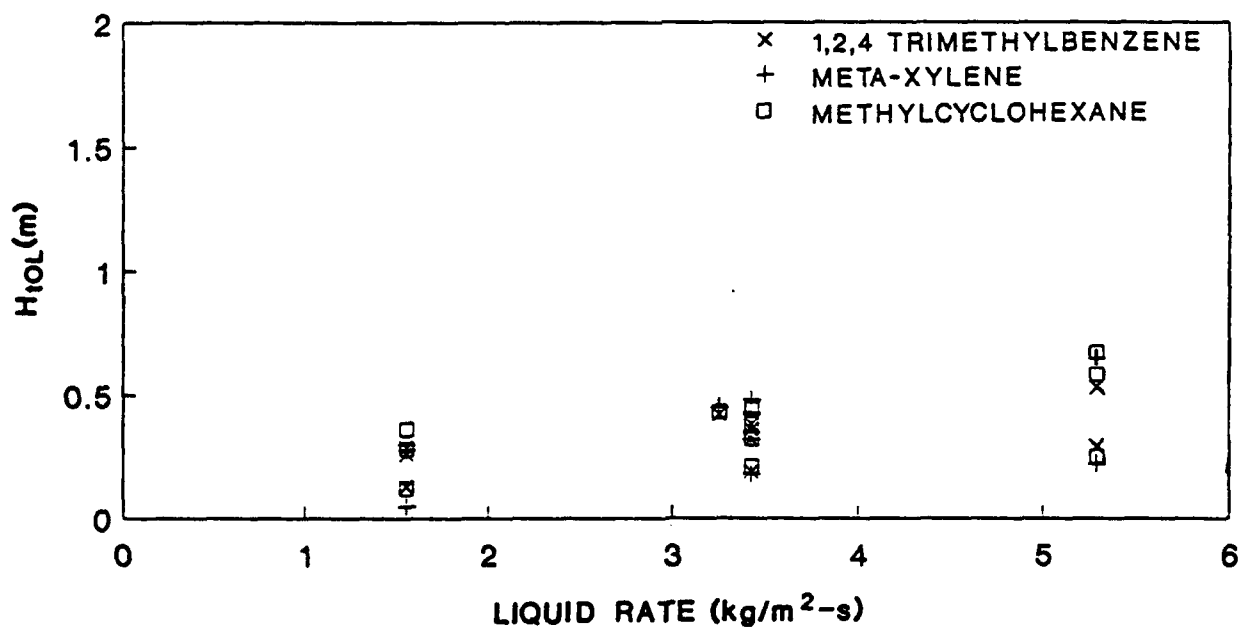


Figure 30. Effect of Liquid Rate on the Experimental  $H_{OL}$  for 1,2,4-Trimethylbenzene, Meta-Xylene, and Methylcyclohexane. (Concluded)

$$Sh = \frac{L' d_{eq}}{H_L \rho_L a_p D_L} \quad (60)$$

When the regressions were executed to determine  $C_1$ ,  $C_2$ , and  $C_3$ , it was found that the term  $C_3$  involving the Schmidt number was not statistically significant for either packing. This result was expected because all of the compounds tested had similar diffusivities at the test conditions, thus making the Schmidt number approximately a constant for this data set. Thus for this data set the constant  $C_1$  and the Schmidt number  $Sc$  can be combined to form a "pseudo" constant  $C'_1$  making the final model:

$$Sh = C'_1 Re_L^{C_2} \quad (61)$$

Both  $C'_1$  and  $C_2$  appeared statistically significant at a 95 percent level for the two packings. Since the Schmidt numbers ranged from 1250 to 1560 (dimensionless), the model could be extrapolated for use in other situations where the Schmidt number is outside this range by dividing  $C'_1$  by  $(1400)^{0.5}$  and multiplying the right-hand-side of Equation (61) by  $Sc^{0.5}$ . The 0.5 power of the Schmidt number is typical of other models in the literature (References 36 and 15). For this packing the regression of Equation (61) produced  $C'_1 = 214.45$  and  $C_2 = 0.287$ . The predictions from this model are shown in Figure 31.

### 3. Koch Flexiramic® Type 48 Packing

Due to time constraints, hydraulic tests were not run on the Flexiramic® packing. The experimental  $H_{OL}$  values for the Koch Flexiramic® packing are shown in Table 16. As with the other packings, the centerpoints were repeated to determine if the packing degraded with time. These points are shown in Figure 32. The change in centerpoint values over the experimental series was not significant when considering the scatter in the data. Unlike the plastic gauze packing, both liquid rate and stripping factor had effects on the  $H_{OL}$  for the Flexiramic® packing. The liquid rate had a strong effect, which is shown in Figure 33. The smaller effect of stripping factor on the  $H_{OL}$  is shown in Figure 34.

Statistical analysis of the experiments showed effects of both liquid rate and stripping factor on the overall  $H_{OL}$ . An empirical model for the  $H_{OL}$  based on a regression of the data is as follows:

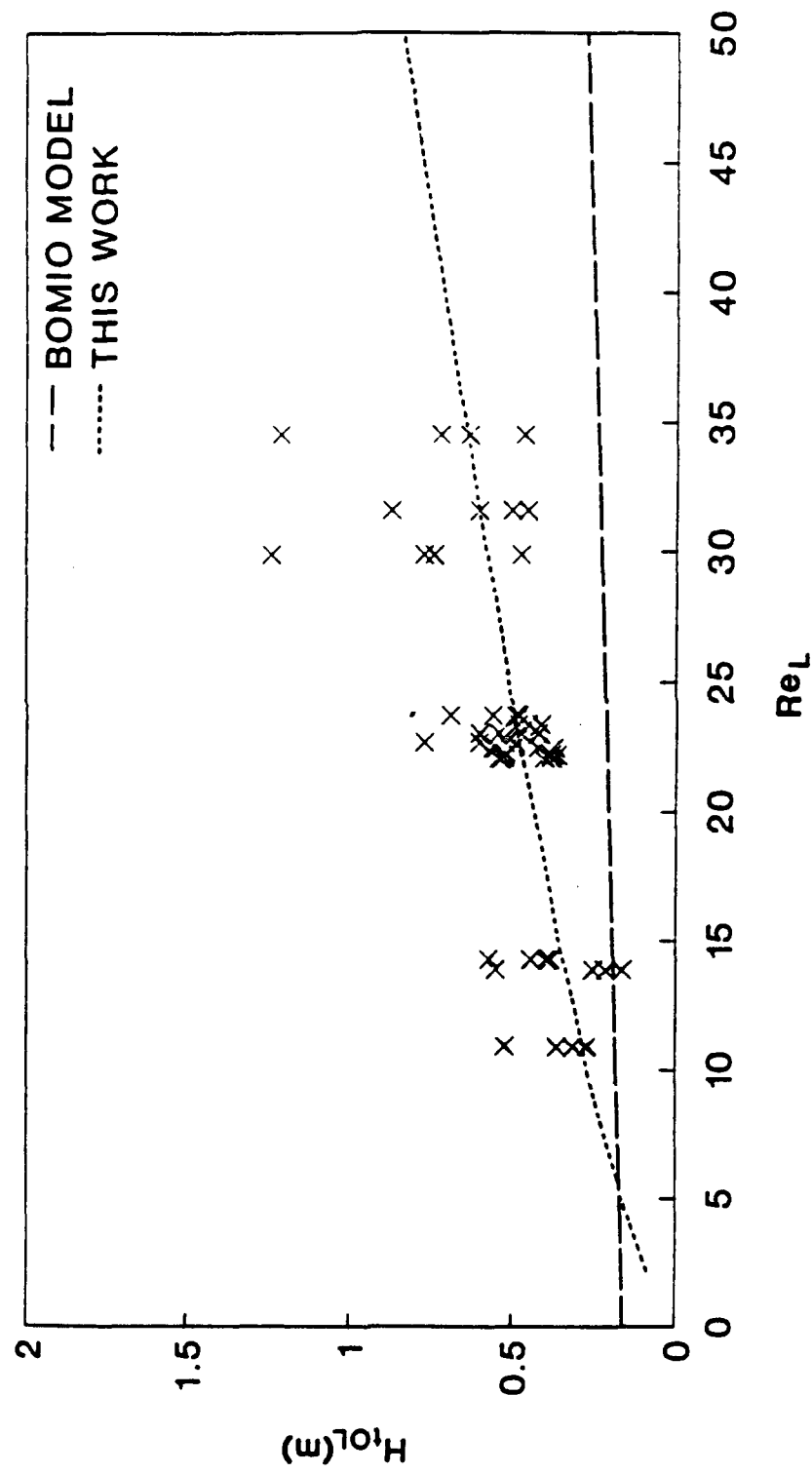


Figure 31. Comparison of Models for  $H_{2O_2}$  with Experimental Data for Koch/Sulzer Type BX Plastic Packing. Models from this Work and from Bomio (Reference 19) are Compared with Experimental Data.

TABLE 16. EXPERIMENTAL  $H_{OL}$  VALUES FOR KOCH FLEXIRAMIC® PACKING

Run #	Liquid Rate $\text{kg/m}^2\text{-s}$	Gas Rate $\text{kg/m}^2\text{-s}$	Toluene		Meta-Xylene		1,2,4-Trimethylbenzene		Naphthalene	
			Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)
1	8.81	0.130	2.51	0.79	2.69	0.82	2.86	0.99	0.20	----
2	14.2	0.110	1.35	0.67	1.45	0.80	1.51	0.96	0.11	----
3	16.7	0.226	2.34	0.80	2.53	0.87	2.62	1.04	0.18	----
4	8.97	0.132	2.56	0.73	2.76	0.80	2.86	0.93	0.20	----
5	1.62	0.027	2.91	----	3.14	0.60	3.29	0.70	2.23	----
6	9.21	0.042	0.80	0.38	0.87	0.45	0.89	0.66	54.00	58.00
7	9.37	0.129	2.43	0.79	2.62	0.69	2.66	0.78	0.19	----
8	3.72	0.079	3.98	0.53	4.32	0.45	4.10	0.46	0.29	----
9	9.13	0.206	3.85	0.68	4.14	0.58	4.39	0.60	0.31	----
10	9.21	0.125	2.33	0.59	2.51	0.50	2.63	0.52	0.19	----
11	14.0	0.277	3.53	0.67	3.82	0.58	3.38	0.60	0.27	----
12	3.88	0.034	1.56	0.35	1.69	0.21	1.68	0.19	0.10	0.19
13	9.21	0.129	2.53	0.54	2.75	0.40	2.69	0.41	0.19	----

Note: Packed height = 1.31 meters and tower cross-sectional area = 0.078  $\text{m}^2$ .

TABLE 16. EXPERIMENTAL  $H_{OL}$  VALUES FOR KOCH FLEXIRAMIC<sup>®</sup> PACKING (CONCLUDED)

Run #	Liquid Rate kg/m <sup>2</sup> -s	Gas Rate kg/m <sup>2</sup> -s	Ortho-Xylene		Pentane		Benzene		Methylcyclohexane	
			Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)
1	8.81	0.130	1.92	0.86	599.70	0.68	2.16	0.69	187.41	0.95
2	14.2	0.110	1.04	0.63	316.19	0.65	1.17	0.64	98.81	0.72
3	16.7	0.226	1.80	0.97	549.11	0.62	2.02	0.75	171.60	0.70
4	8.97	0.132	1.97	0.89	600.48	0.51	2.21	0.66	187.65	0.71
5	1.62	0.027	2.24	0.55	689.86	0.57	2.51	1.44	215.58	1.21
6	9.21	0.042	0.62	0.34	186.28	0.60	0.69	-----	58.21	1.01
7	9.37	0.129	1.87	0.82	557.13	0.58	2.10	0.73	174.10	1.15
8	3.72	0.079	3.10	0.57	859.19	0.51	3.45	0.47	268.50	0.61
9	9.13	0.206	2.95	0.78	920.52	0.56	3.32	0.60	287.66	0.68
10	9.21	0.125	1.79	0.72	552.72	0.52	2.01	0.60	172.73	0.62
11	14.0	0.277	2.72	0.84	804.60	0.48	3.05	0.67	251.44	0.56
12	3.88	0.034	1.21	0.32	352.68	0.43	1.35	0.26	110.21	0.66
13	9.21	0.129	1.95	0.66	565.02	0.61	2.19	0.55	176.57	0.66

Note: Packing height = 1.31 meters and tower cross-sectional area = 0.078 m<sup>2</sup>.

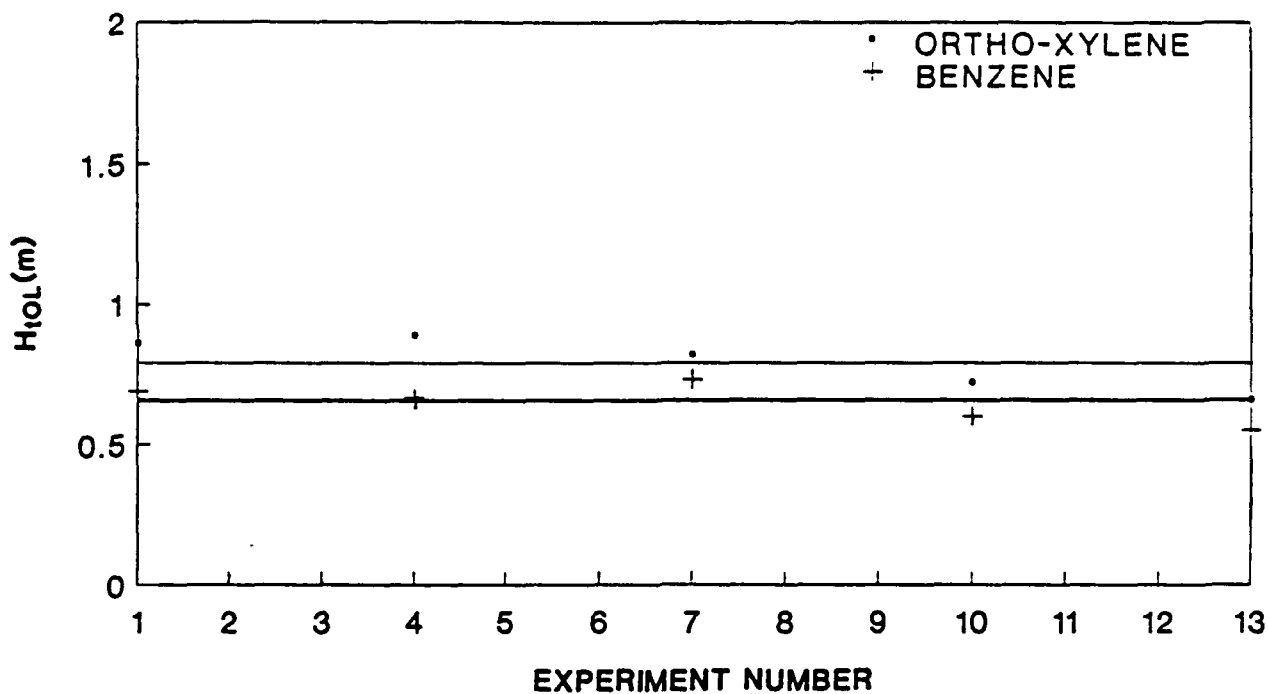


Figure 32. Variation in Experimental Centerpoint  $H_{OL}$  Values for Ortho-Xylene and Benzene from Test with Koch/Sulzer Type BX Plastic Packing.

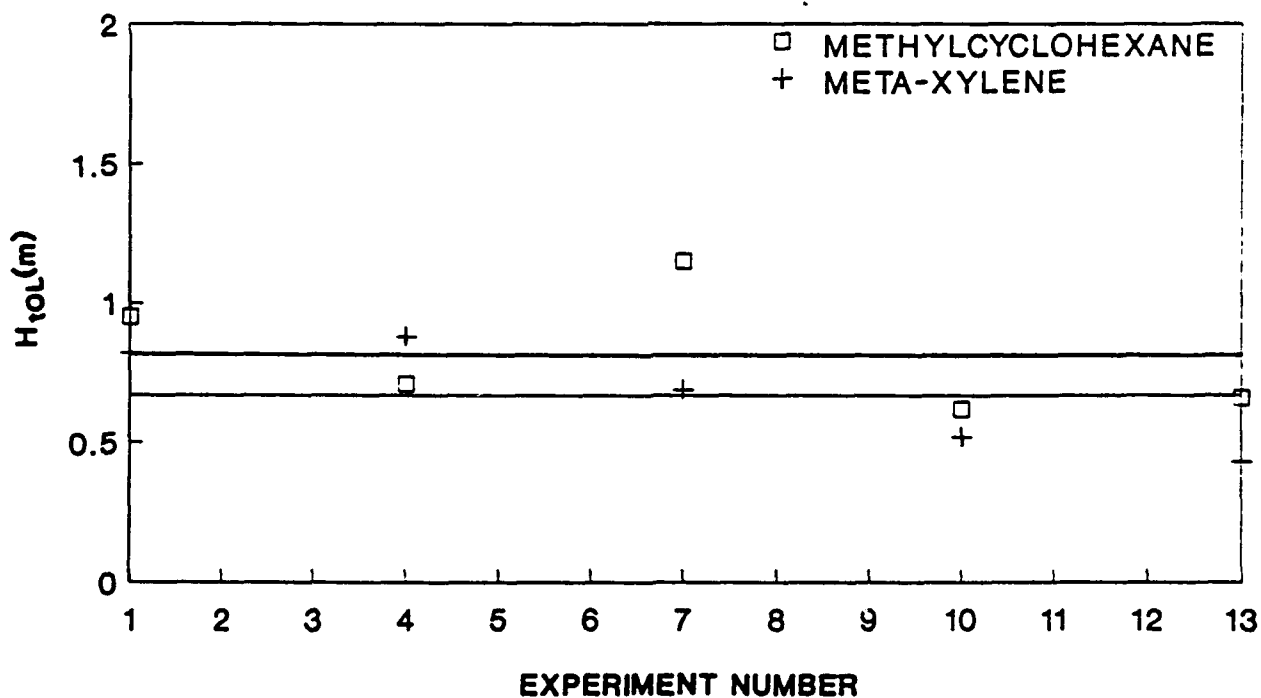


Figure 32. Variation in Experimental Centerpoint  $H_{OL}$  Values for Methylcyclohexane and Meta-Xylene from Tests with Koch/Sulzer Type BX Plastic Packing. (Continued)

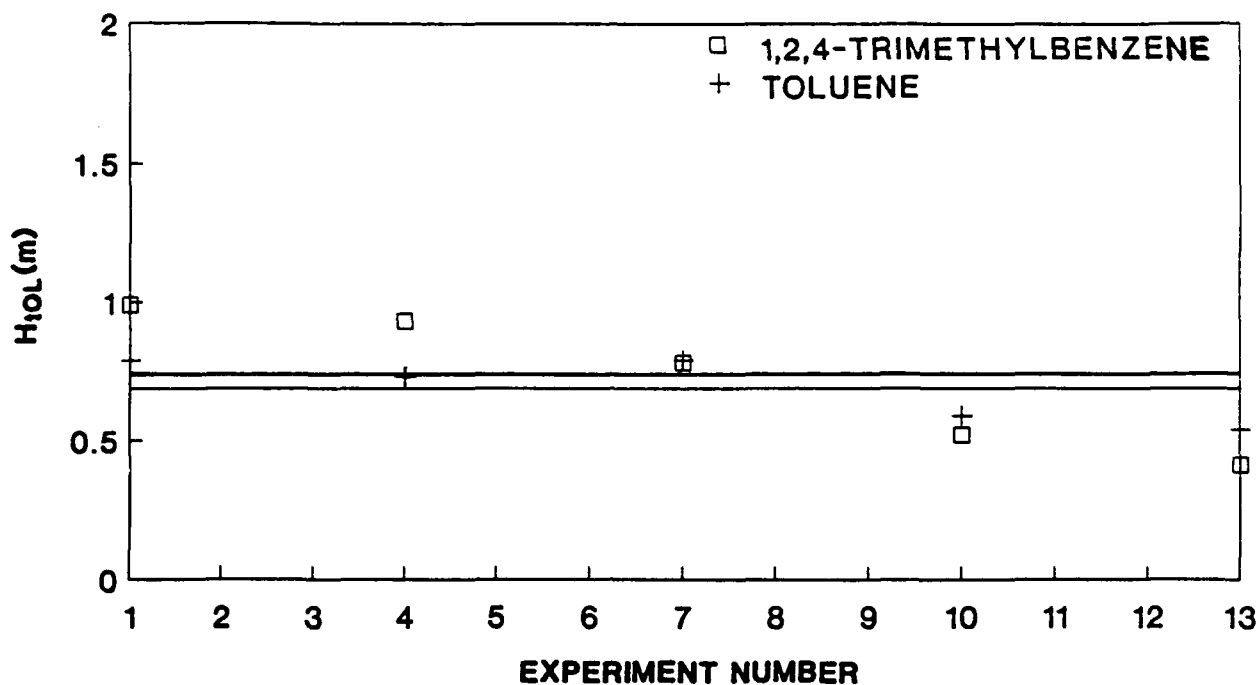


Figure 32. Variation in Experimental Centerpoint  $H_{OL}$  Values for 1,2,4-Trimethylbenzene and Toluene from Tests with Koch/Sulzer Type BX Plastic Packing. (Concluded)

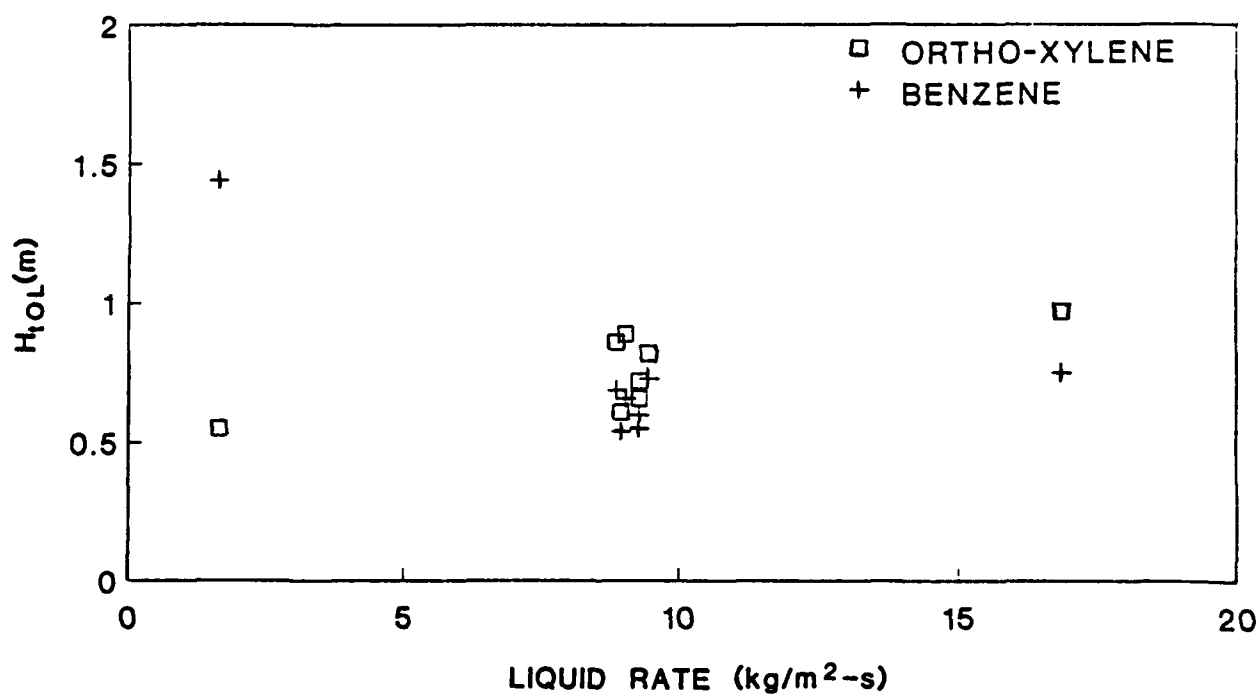


Figure 33. Experimental  $H_{OL}$  for Ortho-Xylene and Benzene vs. Liquid Rate for Koch Flexiramic Packing.

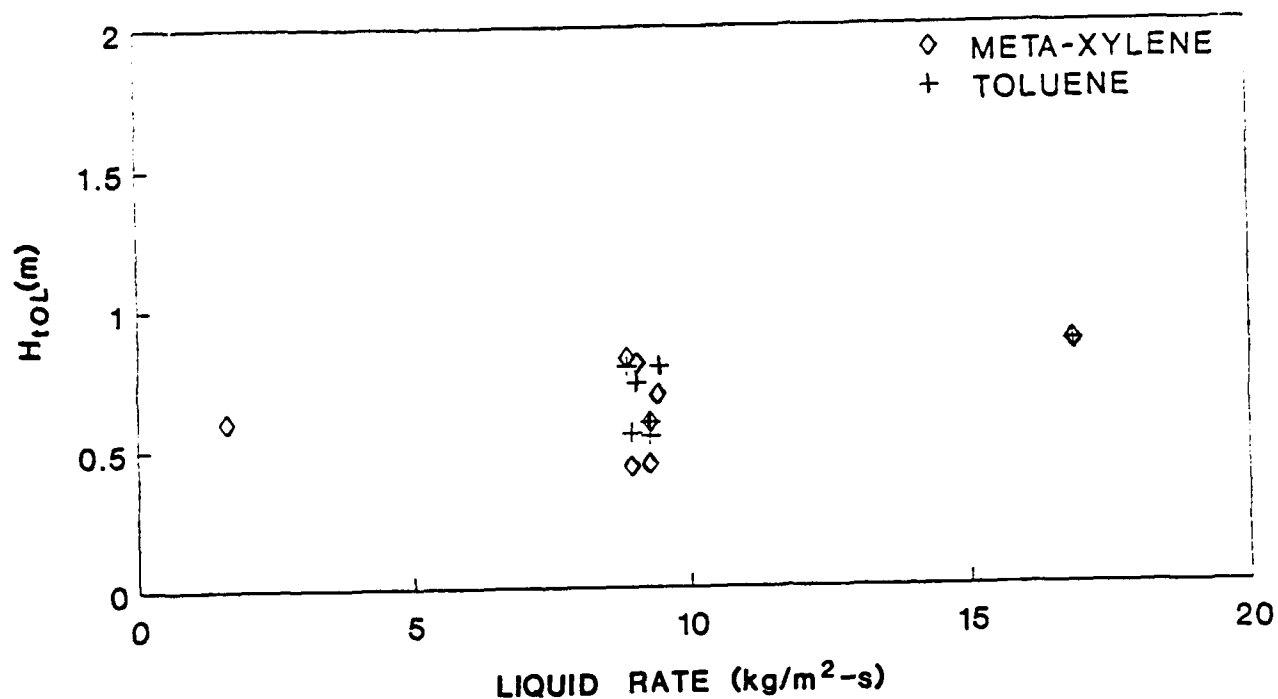


Figure 33. Experimental  $H_{OL}$  for Meta-Xylene and Toluene vs Liquid Rate for Koch Flexiramic Packing. (Continued)

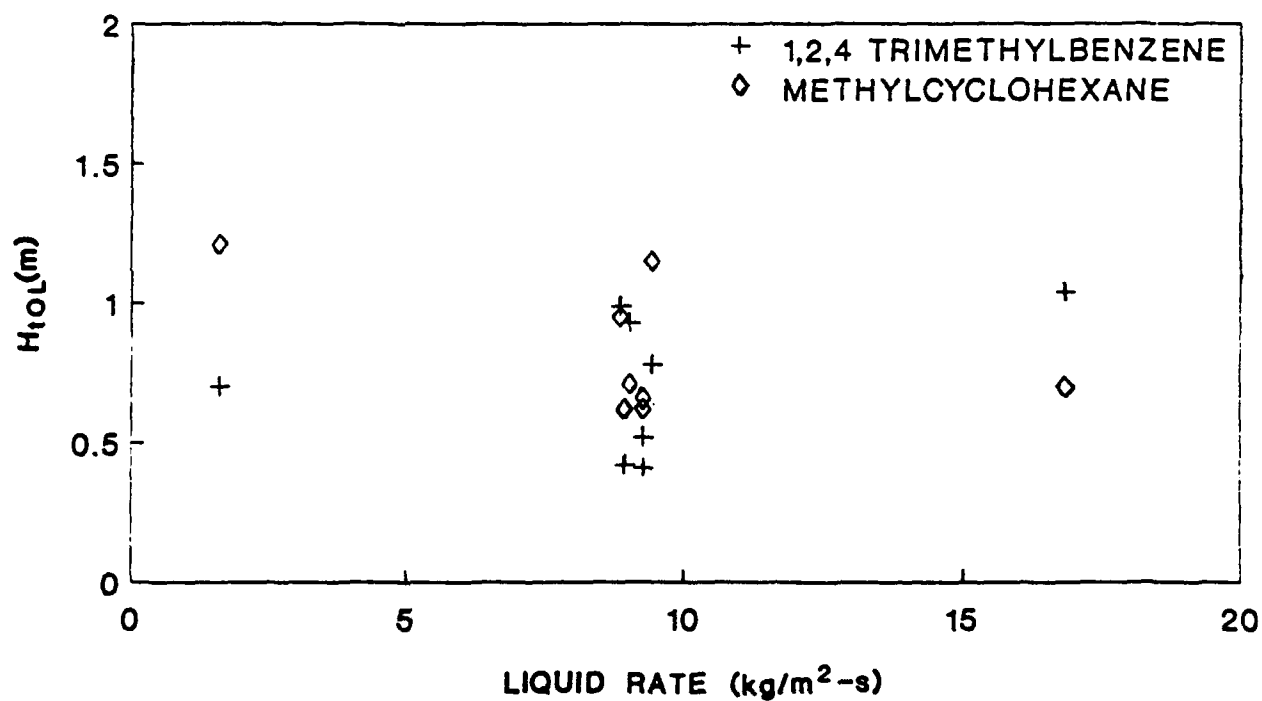


Figure 33. Experimental  $H_{OL}$  for 1,2,4-Trimethylbenzene and Methylcyclohexane vs Liquid Rate for Koch Flexiramic Packing. (Concluded)



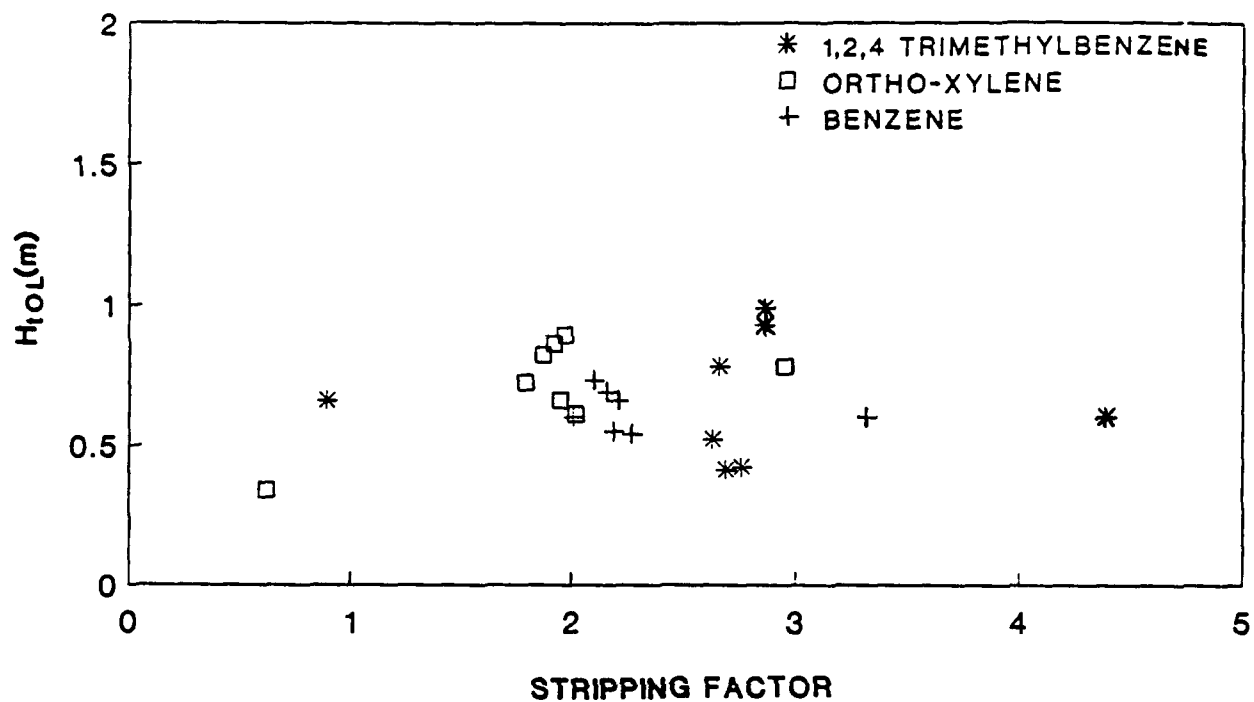


Figure 34. Experimental  $H_{OL}$  for 1,2,4-Trimethylbenzene, Ortho-Xylene, and Benzene vs Stripping Factor for Koch Flexiramic Packing.

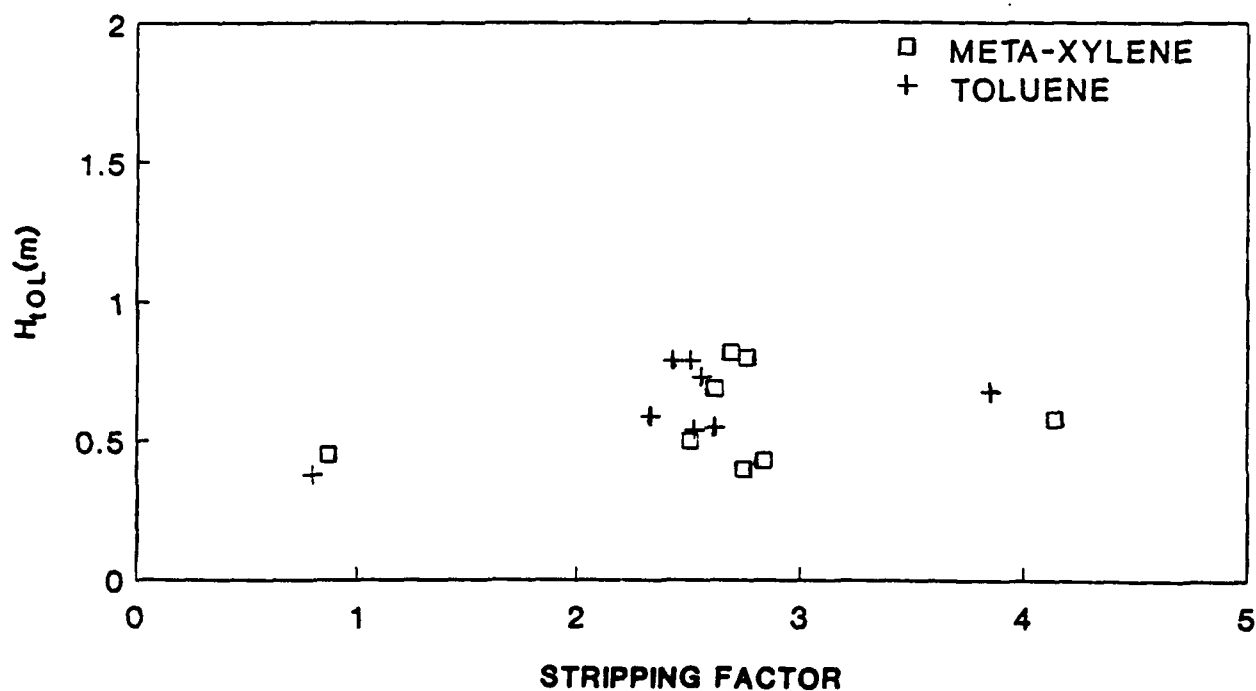


Figure 34. Experimental  $H_{OL}$  for Meta-Xylene and Toluene vs Stripping Factor for Koch Flexiramic Packing. (Continued)

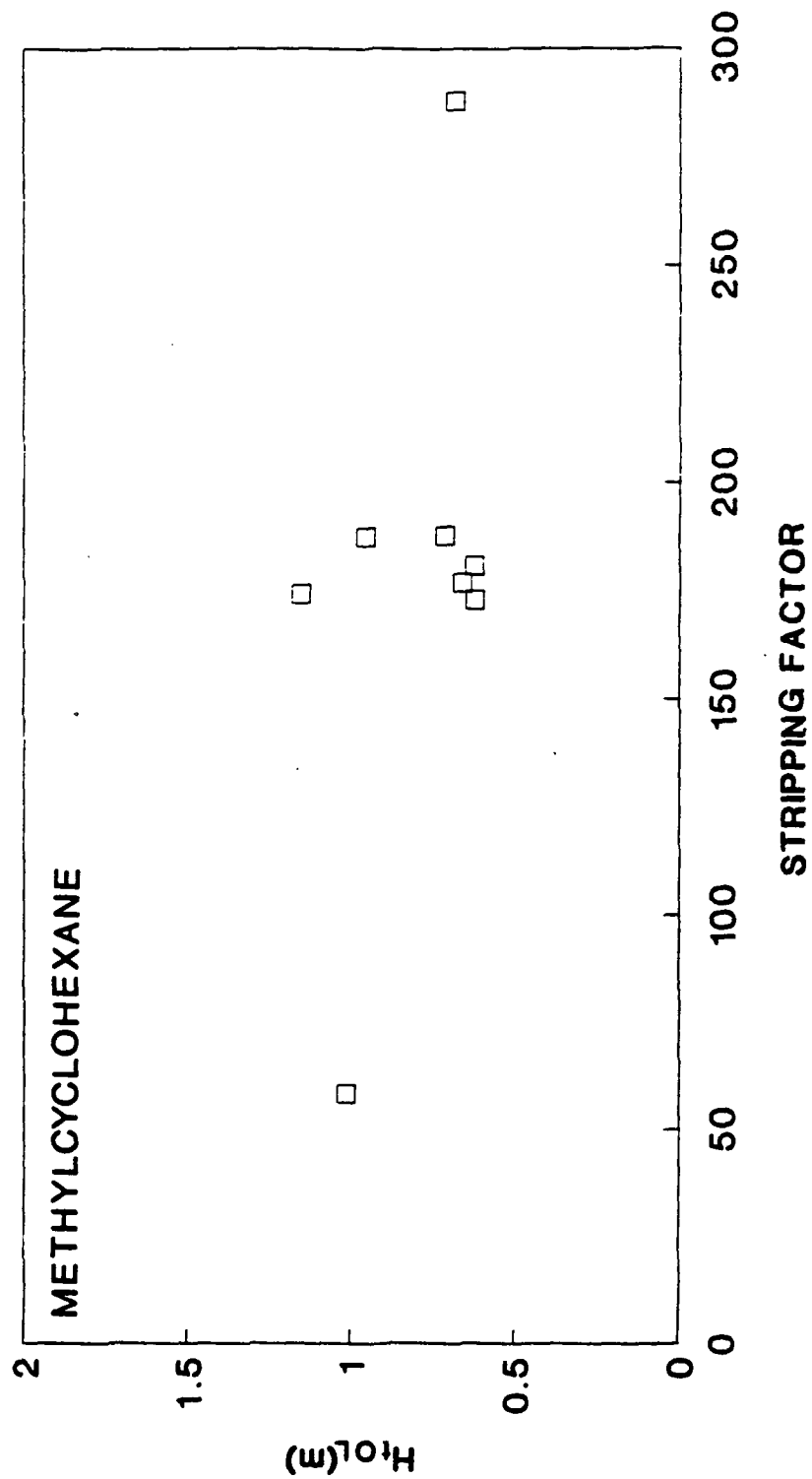


Figure 34. Experimental  $H_{OL}$  for Methylcyclohexane vs Stripping Factor for Koch Flexiramic Packing. (Concluded)

$$H_{iOL} = 1026 * L_v + 0.6 * S - 0.6 \quad (62)$$

A general correlation of the results utilizes the form of Equation (61). The  $H_G$  correlation of Bomio (Reference 19) was used in the determination of  $H_L$  from  $H_{iOL}$  as previously noted. The  $H_G/S$  term was approximately 15 percent of the experimental  $H_{iOL}$  values. The regression of the constants in this equation for this packing produced  $C_1' = 117.42$  and  $C_2 = 0.8105$ . The constants obtained for this packing were different from the Koch/Sulzer. This is attributed to the expectation that the plastic gauze packing is fully wetted, where as the ceramic packing may not be. The predictions for the Flexiramic® packing and those using the model by Bomio (Reference 19) are shown in Figure 35.

#### 4. Delta SH Packing

The pressure drops obtained in the hydraulic tests for Delta SH packing were extremely low compared to the other packings, but comparable to data from Delta Cooling Towers. Due to capacity limits of the blower used, few data points could be obtained for the hydraulic tests. The test results are shown in Figure 36.

Table 17 shows the  $H_{iOL}$  values for the Delta SH packing. The values obtained for this packing were considerably higher (2 meters to 7 meters) than values published by Delta Cooling Towers (0.67 meters). Part of the reason for this difference was later determined to be inadequate distribution of the feed water at the top of the packing. Delta SH packing may be visualized as a "bundle of vertical tubes" with no lateral redistribution characteristics; therefore, initial water distribution is critical for the packing's performance. Unfortunately, the distance from the spray nozzle distributor to the top of the packing was incorrectly specified by Delta Cooling Towers, causing an estimated 15 to 25 percent overspray of water down the walls of the column. Also, the packing was apparently not designed to run at low gas flow rates. Delta Cooling Towers recommends using gas-to-liquid ratios up to 100 times higher (100 to 1200 volume/volume) than those used in these tests. Some experiments were run at higher gas-to-liquid ratios with the correct spray nozzle height. The test results are shown in Table 18. The results do not include the mass transfer which occurs between the spray nozzle and the top of the packing. With this mass transfer included, the "apparent"  $H_{iOL}$  was estimated to range from 0.8 meters to 3 meters for the tests with the correct spray nozzle height. Statistical analysis of the data showed effects of both liquid rate and stripping factor on the  $H_{iOL}$  which indicates the presence of both gas- and liquid-phase resistances.

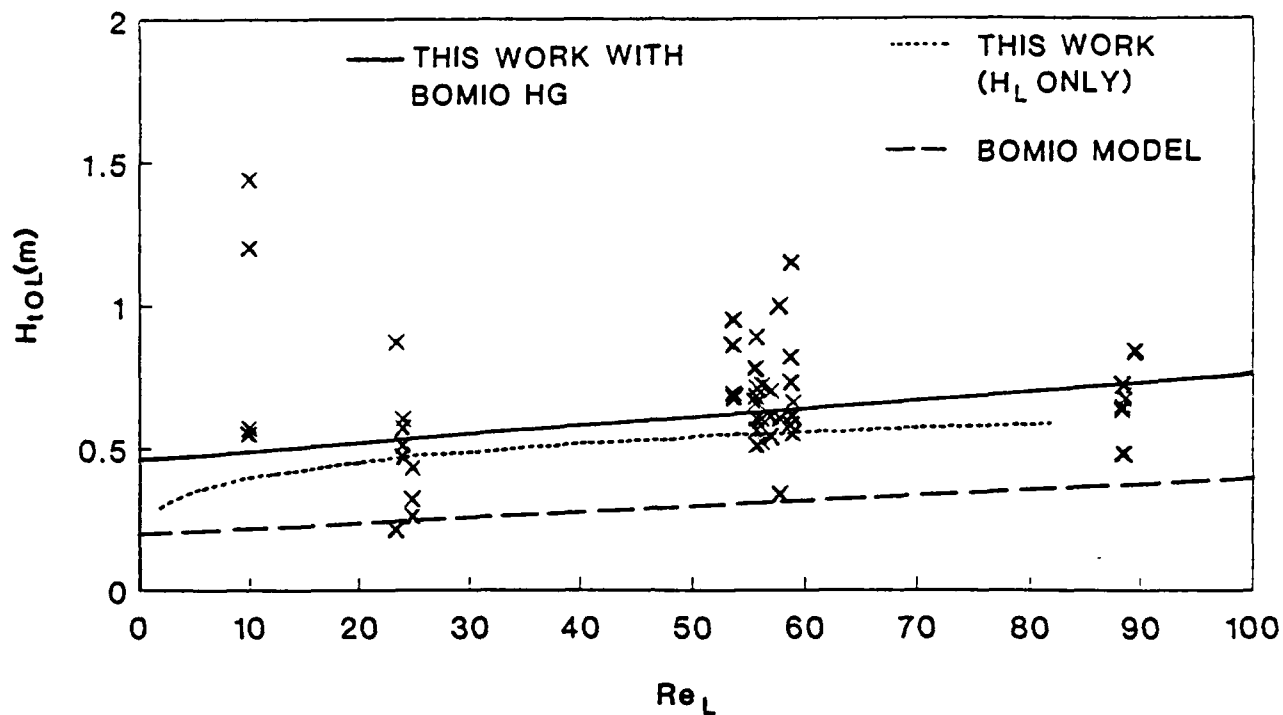


Figure 35. Comparison of Models for  $H_{OL}$  with Experimental Data for Koch Flexiramic Packing. Models from this Work and from Bomio (Reference 19) are Compared with Experimental Data.

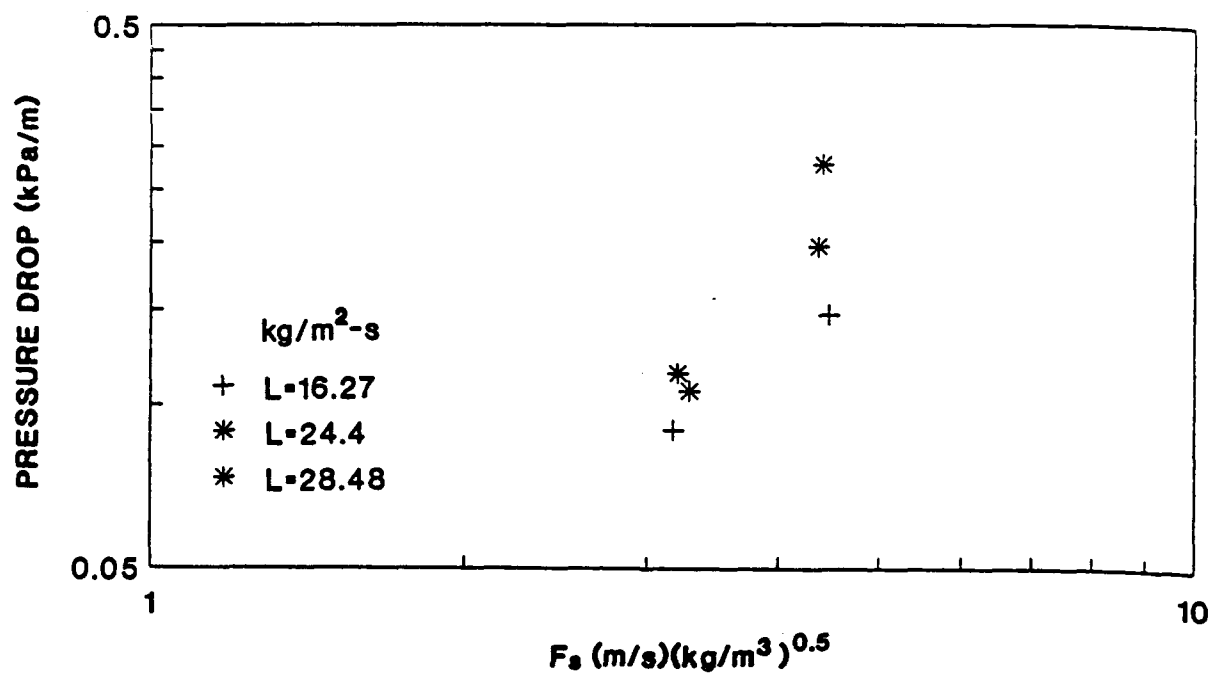


Figure 36. Hydraulic Test for Delta SH Packing.

TABLE 17. EXPERIMENTAL  $H_{OL}$  VALUES FOR DELTA SH PACKING

Run #	Liquid Rate kg/m <sup>2</sup> -s	Gas Rate kg/m <sup>2</sup> -s	Ortho-Xylene		Benzene		Methylcyclohexane		Toluene	
			Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)
1	17.1	0.232	1.78	3.48	1.99	2.24	172.38	1.47	2.31	2.01
2	24.9	0.196	1.02	5.30	1.15	3.01	100.60	1.24	1.33	2.53
3	28.7	0.407	1.87	5.00	2.10	2.97	180.78	1.42	2.43	3.20
4	16.9	0.236	1.86	3.28	2.09	2.58	177.86	1.30	2.42	2.18
5	5.25	0.074	1.88	1.95	2.12	1.49	180.20	1.20	2.45	1.49
6	17.0	0.103	0.80	7.35	0.90	5.93	76.52	3.91	1.05	7.89
7	17.0	0.242	1.86	4.81	2.09	3.12	180.92	2.35	2.43	3.13
8	8.24	0.176	2.82	2.61	3.17	2.52	270.85	1.83	3.67	2.00
9	17.0	0.366	2.85	4.28	3.20	2.87	273.15	3.98	3.70	4.41
10	17.1	0.236	1.82	3.69	2.04	2.64	175.17	1.41	2.37	2.56
11	25.1	0.496	2.66	3.62	2.99	2.50	250.60	1.13	3.46	2.25
12	8.65	0.066	0.99	3.58	1.11	2.08	97.02	1.39	1.29	2.26
13	17.2	0.240	1.85	3.36	2.07	2.21	177.24	1.25	2.40	2.27

Note: Packed Height = 2.9 meters and tower cross-sectional area = 0.078 m<sup>2</sup>.

TABLE 17. EXPERIMENTAL  $H_{OL}$  VALUES FOR DELTA SH PACKING (CONCLUDED)

Run #	Liquid Rate kg/m <sup>2</sup> -s	Gas Rate kg/m <sup>2</sup> -s	Meta Xylene		1,2,4-Trimethylbenzene		Naphthalene	
			Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)	Stripping Factor	$H_{OL}$ (m)
1	17.1	0.232	2.49	2.85	2.63	3.38	0.19	-----
2	24.9	0.196	1.43	4.11	1.53	5.12	0.11	-----
3	28.7	0.407	2.62	3.97	2.76	4.84	0.19	-----
4	16.9	0.236	2.61	2.73	2.71	3.28	0.19	-----
5	52.5	0.074	2.64	1.69	2.75	1.99	0.19	-----
6	17.0	0.103	1.13	6.28	1.17	7.04	0.08	14.26
7	17.0	0.242	2.61	3.69	2.76	4.32	0.19	-----
8	8.24	0.176	3.96	2.25	4.13	2.69	0.29	11.38
9	17.0	0.366	3.99	3.81	4.17	4.22	0.30	27.28
10	17.1	0.236	2.55	3.10	2.67	3.74	0.19	42.90
11	25.1	0.496	3.73	3.03	3.82	3.72	0.27	-----
12	8.65	0.066	1.38	2.96	1.48	3.95	0.10	17.30
13	17.2	0.240	2.59	2.88	2.70	3.83	0.19	104.00

Note: Packing Height = 2.9 meters and tower cross-sectional area = 0.078 m<sup>2</sup>.

TABLE 18. EXPERIMENTAL  $H_{OL}$  VALUES FOR DELTA SH PACKING HIGH STRIPPING FACTORS

Run #	Liquid Rate $\text{kg/m}^2\text{-s}$	Gas Rate $\text{kg/m}^2\text{-s}$	Ortho- Xylene $H_{OL}$ (m)	Benzene $H_{OL}$ (m)	Methylcyclo- Hexane $H_{OL}$ (m)	Toluene $H_{OL}$ (m)	Meta- Xylene $H_{OL}$ (m)	1,2,4- Trimethylbenzene $H_{OL}$ (m)
1	15.8	1.07	3.58	3.45	7.92	4.24	3.12	3.14
2	15.8	2.03	2.96	2.95	7.19	3.69	2.86	2.85
3	15.9	0.235	5.06	3.50	4.81	4.75	3.96	3.96
4	28.3	1.74	2.95	2.14	1.27	2.24	2.42	2.63
5	27.6	3.95	2.02	1.59	1.34	2.02	1.75	1.88
6	5.25	0.734	1.04	1.00	1.04	1.21	0.96	1.04
7	5.25	0.328	1.38	1.23	1.33	1.40	1.23	1.26

Note: Tower cross-sectional area =  $0.078 \text{ m}^2$ .

## 5. Packing Comparison

The heights of a transfer unit for the high efficiency Koch/Sulzer packing were roughly 60 percent of those for Flexirings®. Although the  $H_{OL}$  for the Koch Flexiramic® packing were comparable to those observed for Flexirings®, its capacity is expected to be higher (Reference 38). Figure 37 shows a comparison of the packings at constant stripping factor. The Delta SH Packing is not included in this comparison; problems encountered in the experiments with this packing were previously discussed.

## B. CENTRIFUGAL AIR STRIPPER

### 1. Mass Transfer Results and Discussion

#### a. Mass Transfer Performance

Since very few data on the mass transfer performance of a centrifugal vapor-liquid contactor were available during the design phase of this project, it was decided that three rotors containing Sumitomo packing with varying outer radii would be used to determine the concentration profiles. The inner radius and the axial length of all three rotors would be identical. The operating conditions were chosen to include as wide a range as possible with respect to the limitations of the ancillary equipment.

#### b. General Characteristics

The accuracy of the mass transfer data can be affected by large variations in the composition of the feed material. The groundwater at Eglin AFB had been pumped for several years, and the concentration of VOCs in the water was expected to be relatively constant. The well pumps were left running during this entire project to promote steady-state movement of the groundwater in the vicinity of the spill area. The composition of the feed water during the mass transfer tests with the 45.92 cm diameter rotor is shown in Figure 38. The data in Figure 38 represent a time span of approximately 2 weeks and show that the variations in the feed water composition were relatively minor.

One problem in characterizing the mass transfer performance of a packing torus is separating the mass transfer that occurs inside the packing from that which occurs outside the packing (end effects). The use of three rotors and a special sampling system were proposed as possible solutions to the problem. In the case of the 76.20 cm diameter rotor, the  $N_{OL}$  was so large at the majority of the operating conditions that very high removals were achieved. Measuring very low concentrations (less than 1 ppb) in the exit water stream introduced a large degree of uncertainty in the final results. In addition, the anomalous pressure drop behavior of the 60.96 cm diameter rotor



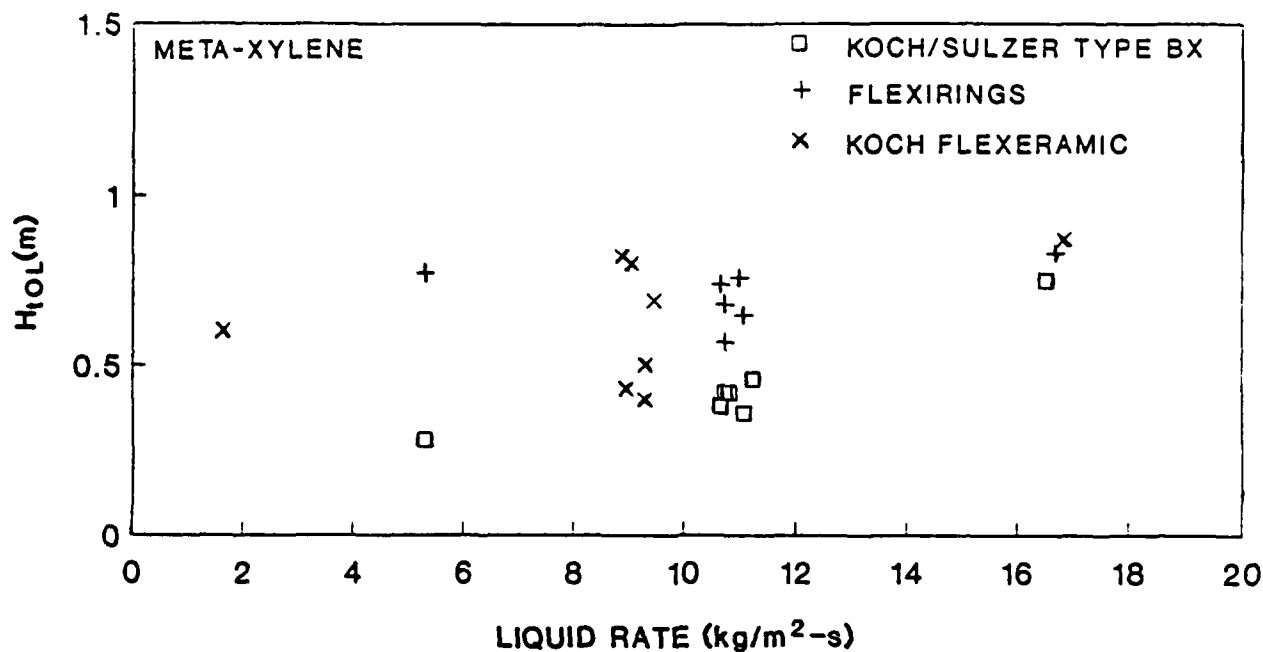


Figure 37. Comparison of Experimental  $H_{OL}$  Packings Used in the Study for Meta-Xylene Removal.

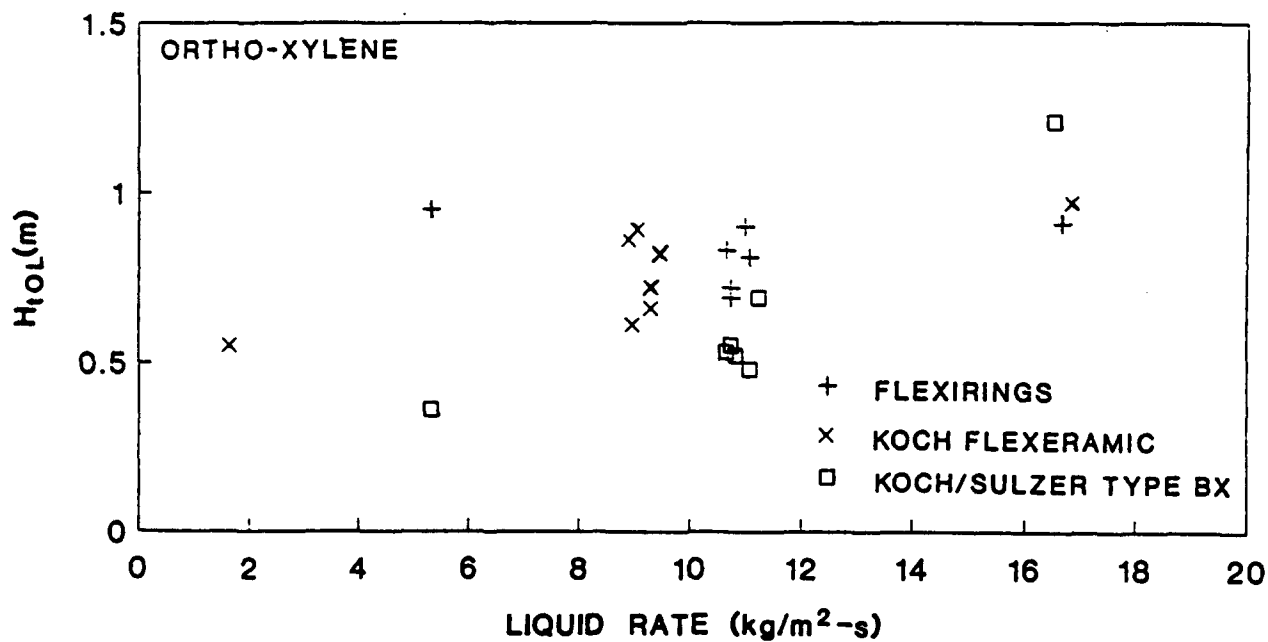


Figure 37. Comparison of Experimental  $H_{OL}$  Packings Used in the Study for Ortho-Xylene Removal. (Concluded)

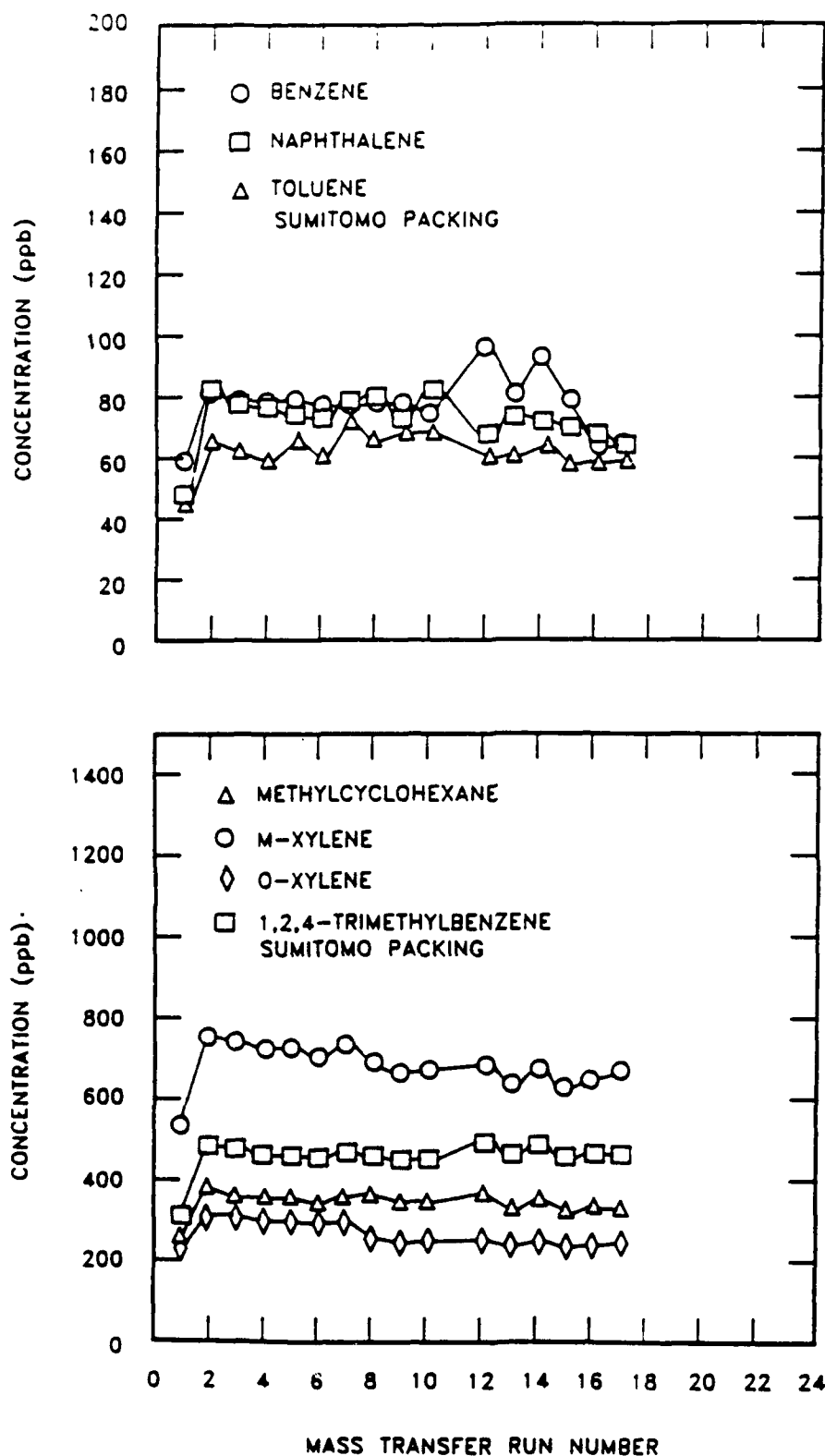


Figure 38. Variation in the Feed for the Mass Transfer Tests with the 45.73 cm Diameter Rotor.

made the mass transfer results from this rotor questionable. Consequently, it was decided that a good estimate of end effects could only be obtained from those operating conditions where the exit water stream concentrations for the 76.20 cm diameter rotor were high enough (10 ppb) to be measured accurately. There were only 4 runs out of 15 in which such high concentrations were observed, and the results from two of these runs are plotted in Figure 39. Statistical analysis of the four runs indicated that the intercept, which is a measure of end effects, was not significantly different from zero. Thus, the conclusion was that the sampling system had effectively eliminated the end effects. It is interesting to note that the pattern of data for both sets of conditions in Figure 39 is almost identical and only the slope is different. The data from all the centerpoint runs are shown in Figure 40. Although this plot indicates that there are some end effects, this is probably due to the uncertainty in the  $N_{\text{OL}}$  values from the 76.20 cm diameter rotor where concentrations were all below 1 ppb. This figure shows that, even with the uncertainties associated with the analytical analysis, the  $N_{\text{OL}}$  measured in the 76.20 cm diameter rotor seems reasonable.

The conclusion that the sampling system was successful in eliminating the end effects allows the data from each rotor to be analyzed independently. Since the concentration in the exit water stream from all the tests with the 45.92 cm diameter rotor were well above the detection limit of the analytical equipment, these data were analyzed in greatest detail. Figure 40 shows the reproducibility for the center point runs with the 45.92 cm diameter rotor. The coefficient of variation for the  $N_{\text{OL}}$  (o-xylene data) was 8 percent for the Sumitomo packing and 6.4 percent for the wire gauze packing.

The effect of acceleration on the  $A_{\text{OL}}$  for the 45.72 cm diameter rotor is shown in Figure 41. The  $A_{\text{OL}}$  decreases with an increase in acceleration for both types of packings. The decrease in  $A_{\text{OL}}$  appears to level out at accelerations greater than 1000 meters/s<sup>2</sup>. Also shown in Figure 41 is a data point from the 76.20 cm diameter rotor. Notice that this rotor gives a considerably higher  $A_{\text{OL}}$  than the 45.92 cm diameter rotor at the same operating conditions. This increase in  $A_{\text{OL}}$  with outer rotor radius may indicate incomplete wetting of the packing at the outer edge. This phenomenon was investigated further by comparing data at other conditions. Since only four runs were available for the 76.92 cm diameter rotor, the comparison was rather limited. Figure 42 shows  $A_{\text{OL}}$  values for two run conditions. From this figure, at a low rotational speed (500 rpm) there appears to be a significant difference between the  $A_{\text{OL}}$  values for the two rotors,

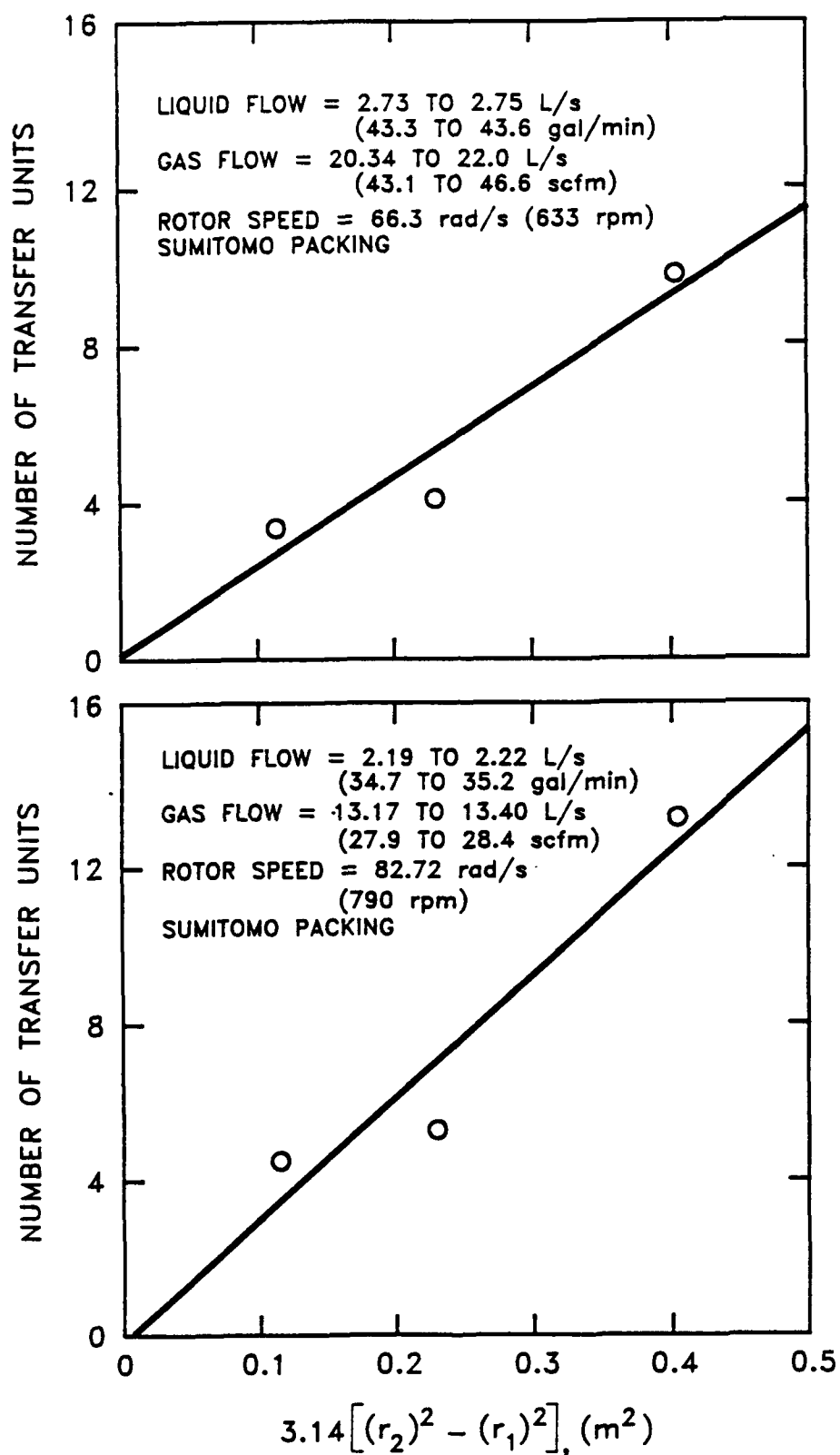


Figure 39. Plot of Mass Transfer Data to Determine End Effects (O-Xylene Data).

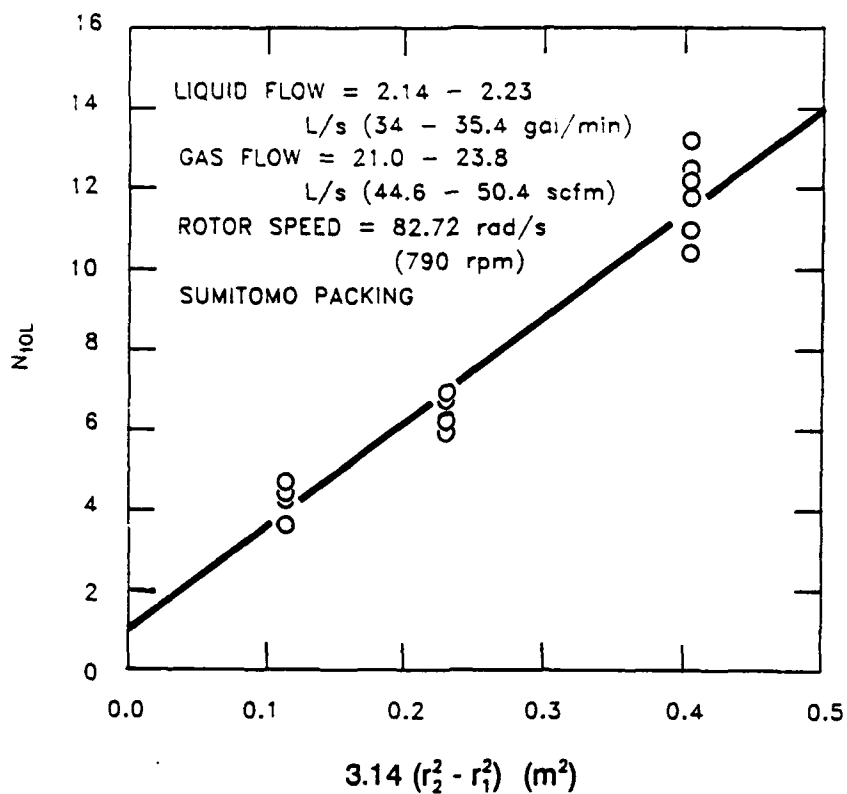


Figure 40. Plot of Mass Transfer Data from Centerpoint Runs (O-Xylene Data).

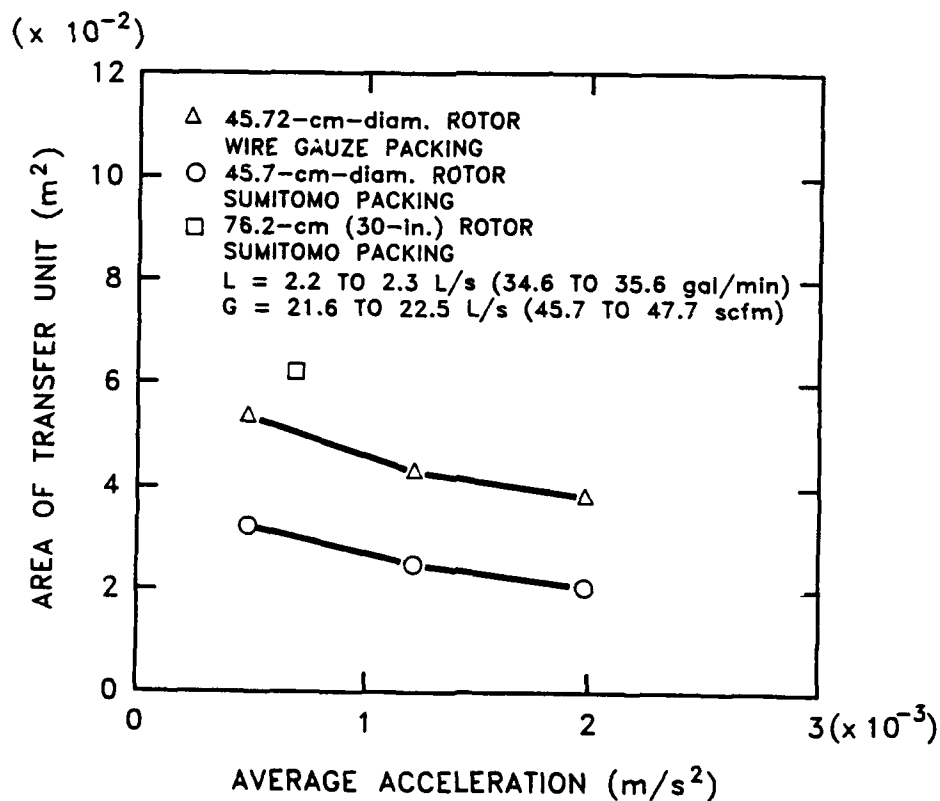


Figure 41. Effect of Acceleration on the  $A_{OL}$  (O-Xylene Data).

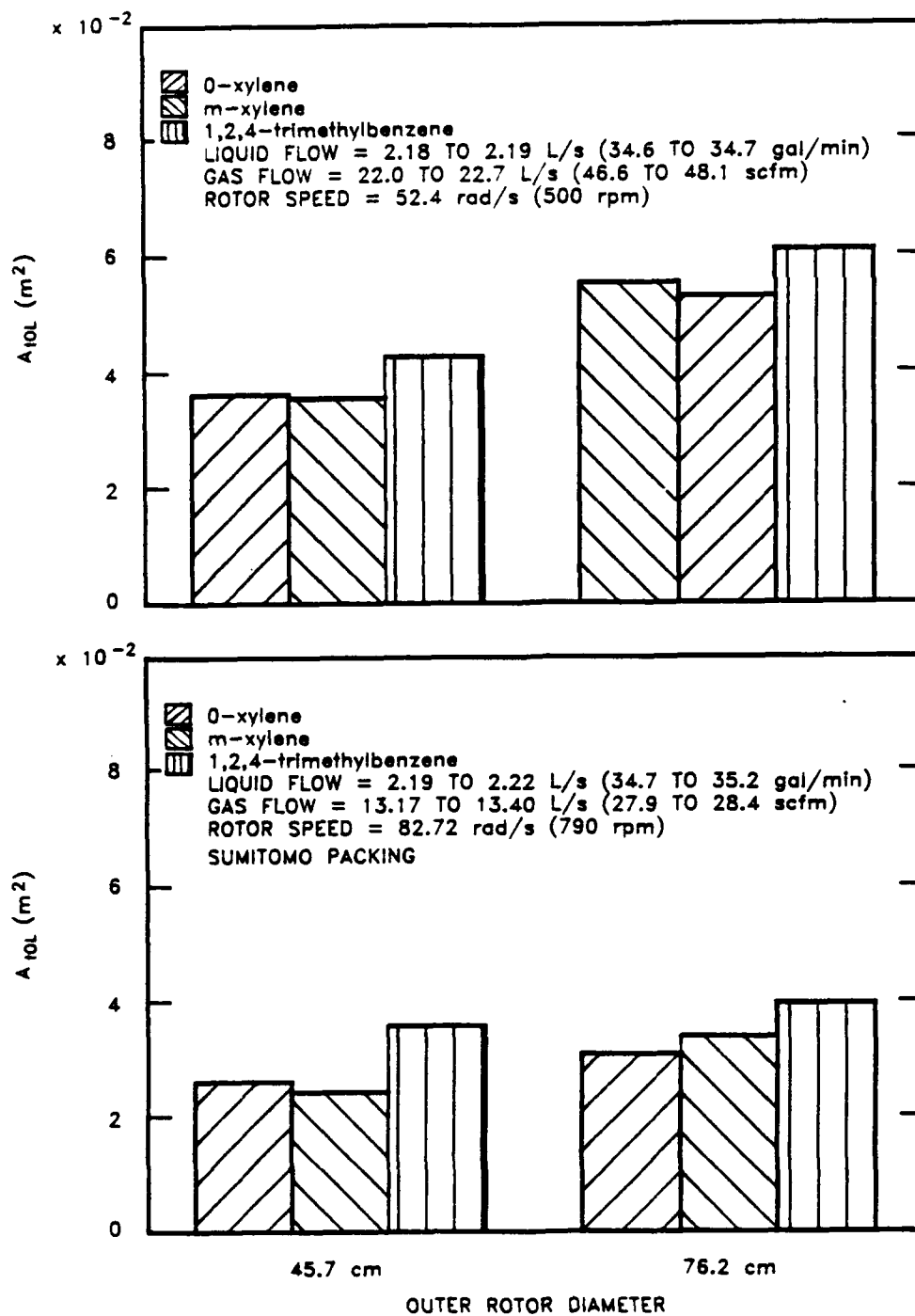


Figure 42. Comparison of  $A_{10L}$  for the Different Rotors.

while at 790 rpm the difference is relatively minor. Thus, it might be argued that, to achieve the same value of an  $A_{\text{OL}}$ , the large diameter rotor would have to be operated at higher speeds, which leads to higher operating costs.

The effect of liquid flow rate and gas/liquid ratio on the  $A_{\text{OL}}$  is shown in Figures 43 and 44, respectively. Both types of packing exhibit an analogous behavior. The  $A_{\text{OL}}$  is seen to increase with liquid flow rate. This behavior would be expected since the mass transfer rate of the three compounds is liquid film controlled and the thickness of the liquid film increases with an increase in the liquid flow rate. The effect of the gas/liquid ratio on  $A_{\text{OL}}$  appears to be negligible for o-xylene and m-xylene with the Sumitomo packing. While results from the wire gauze packing shows greater scatter for these two compounds, the change in  $A_{\text{OL}}$  is still rather small. The  $A_{\text{OL}}$  for 1,2,4-trimethylbenzene increases at low gas/liquid ratio for both packings. As in the case of the packed column, this increase in  $A_{\text{OL}}$  could be a consequence of approaching equilibrium conditions. As discussed previously, the calculated  $N_{\text{OL}}$  is very sensitive to the stripping factor near equilibrium conditions. Therefore, the behavior of the  $A_{\text{OL}}$  could be due to the uncertainty in the stripping factor, particularly as effected by the Henry's Law constant.

### c. Experimental Design Analysis

The central composite design was analyzed to determine which independent variables had a significant effect on the area of transfer unit. The following general linear model was used in the analysis:

$$A_{\text{OL}} = Z_0 + Z_1 L + Z_2 a_c + Z_3 (G_v/L_v) + Z_4 L_v^2 + Z_5 a_c^2 + Z_6 (G_v/L_v)^2 + Z_7 L_v a_c + Z_8 L_v (G_v/L_v) + Z_9 a_c (G_v/L_v) \quad (63)$$

where  $Z_0 \dots Z_9$  are regression coefficients. Table 19 shows the terms in Equation (63) which were significant at the 95 percent confidence level for o-xylene. O-xylene data were used in this analysis because the o-xylene peak on the chromatogram was very distinct and had no side peaks which could give erroneous measurements. For both packings, the variance of the repeated center point runs was less than that observed for the whole model. This implies that the change in  $A_{\text{OL}}$  with operating conditions was real and not just due to the scatter in the observed data.

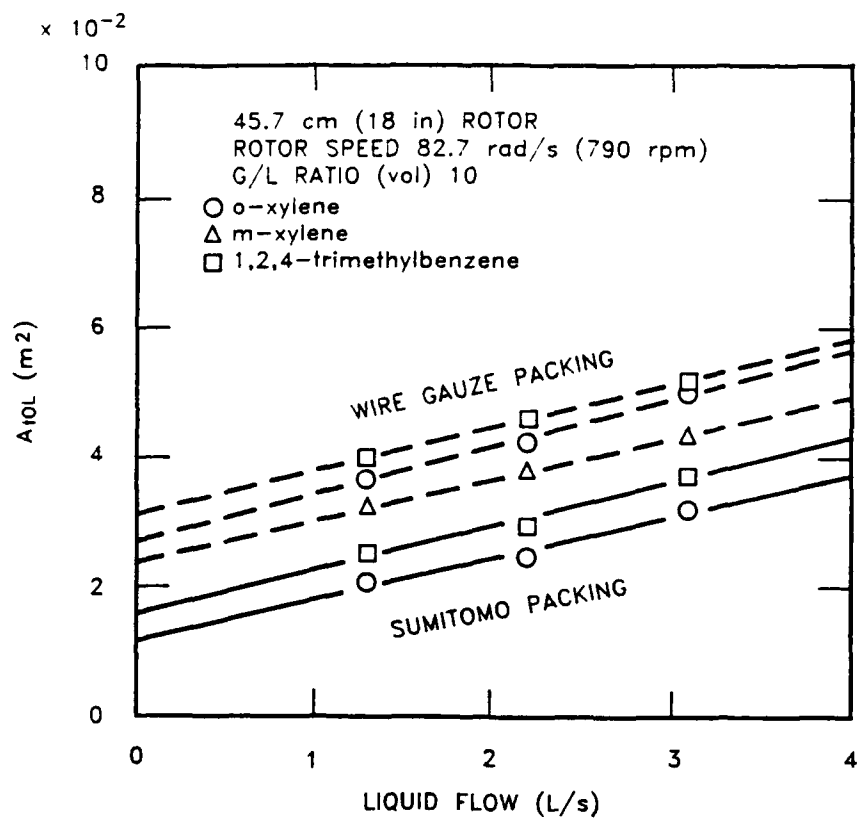


Figure 43. Effect of Liquid Flow on the  $A_{OL}$ .

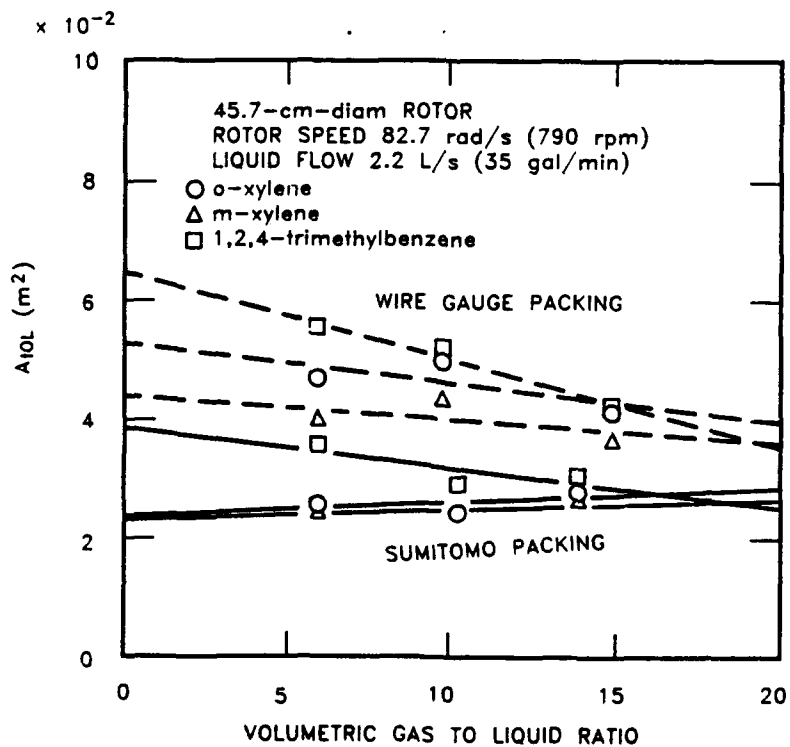


Figure 44. Effect of Gas/Liquid Ratio on  $A_{OL}$ .



TABLE 19. RESULTS OF CENTRAL COMPOSITE EXPERIMENT DESIGN ANALYSIS

PACKING	TERMS WITH SIGNIFICANT EFFECT
Sumitomo	$a_c^2$
	$a_c L_v$
Wire Gauze	$a_c$
	$L_v$
	$a_c L_v$
	$L_v(G_v/L_v)$

In order to reduce the number of terms in the above model, a SAS regression procedure was used. In this analysis, independent variables are added to the model one-by-one if the corresponding F statistic for a variable is significant at a prescribed level. Each time a variable is added, the variables already in the model are examined and those that do not produce a significant F statistic are eliminated. The entrance and elimination levels used are somewhat arbitrary. For this work, the default entrance and elimination levels of 0.15 given in SAS were used. The final model for the Sumitomo packing produced by this technique is:

$$A_{\text{vol}} = 0.031 - 8.6 \times 10^{-6} a_c + 4.7 \times 10^{-9} a_c^2 + 1.3 \times 10^3 L_v^2 - 3.8 \times 10^{-3} a_c L_v - 5.4 \times 10^{-7} a_c (G_v/L_v) + 4.0 \times 10^{-1} L_v (G_v/L_v) , \quad (64)$$

and the model for the wire gauze packing is:

$$A_{\text{vol}} = 0.037 + 8.1 L_v - 8.3 \times 10^{-7} a_c (G_v/L_v) . \quad (65)$$

The coefficients of determination ( $r^2$ ) for the two models were 0.96 and 0.75, respectively. Although these models can be used to design a centrifugal vapor-liquid contactor for conditions similar to those in this study, it would be beneficial to develop a general correlation similar to those used for conventional packed towers.

#### d. Comparison of the Data with Existing Correlations

As stated earlier, two correlations have been proposed for possible use in modeling the mass transfer performance of a centrifugal vapor-liquid contactor. One was given in Equation (36) as

$$\frac{k_L a d^2}{D_L} = 0.023 Sc^{1/2} Gr^{0.38} (dL'/\mu_L)^{1/2} * (1 - 1.02 \exp[-0.15(dL'/\mu_L)^{0.4}]) ,$$

and the other, Equation (35), was

$$\frac{k_L d}{D_L} = 0.96 Sc^{1/2} Re^{1/3} (a_i/a_w)^{1/3} Gr^{1/6} .$$

Both of these equations require a characteristic dimension for the packing. In evaluating the predictive capability of the correlations, the characteristic dimension for the Sumitomo packing was taken to be the thickness (0.002 meters) of one sheet of packing. For the wire gauze packing, the total thickness of the packing (0.1 meters) was used since no other dimension was available. In addition, average values for acceleration and liquid loading were used. Average velocities may be calculated using:

$$AVG f_{[a,b]} = \frac{1}{b-a} \int_a^b f dr , \quad (66)$$

where  $f$  is the gas or liquid velocity. For liquid velocity, this equation becomes:

$$AVG V = \frac{1}{r_2 - r_1} \int_{r_1}^{r_2} \frac{L_v}{2 \pi r l} dr , \quad (67)$$

where  $L_v$  is the volumetric liquid flow rate and  $l$  is the axial length of the packing. The diffusion coefficient for o-xylene in water was calculated using the Wilke-Chang equation (Reference 39).

The  $A_{iOL}$  calculated using Equation (36) is compared with the experimental values in Figure 45. This correlation over predicts the value of the  $A_{iOL}$  by a factor of 3 to 5. The results of a similar comparison for Equation (35) are given in Figures 46 and 47. Two values of the interfacial area were used. First, it was assumed that the interfacial area was equal to the total specific surface area of the packing. For the second set of calculations, the equation given by Onda et al. (Reference 15) for the interfacial area was used. This correlation seems to do a reasonable job in predicting the  $A_{iOL}$  for the Sumitomo packing, but it overestimates the values for the wire gauze packing. As expected, this suggests that choice of characteristic length is very important. It also suggests that the reasonable prediction for the Sumitomo packing was just a coincidence, since a packing with similar characteristics could be fabricated out of different thickness material. Thus, it was concluded that these two correlation are not appropriate for use with the type of packings used in this study.

#### e. New Correlation Based on Specific Surface Area of Packing

Because existing correlations were unable to predict the  $A_{iOL}$  of the centrifugal vapor-liquid contactor, a new correlation, which uses the specific surface area of packing instead of characteristic length, was developed. The correlation was developed assuming that the  $A_{iOL}$  is a function of the following variables: liquid mass velocity ( $L'$ ), liquid viscosity ( $\mu_L$ ), liquid density ( $\rho_L$ ), specific surface area of packing ( $a_i$ ), and acceleration ( $a_c$ ). This function can be written as:

$$A_{iOL} = f(L', \mu_L, \rho_L, a_i, a_c) \quad (68)$$

Using Buckingham's Pi Theorem, these variables can be combined into dimensionless groups. This method is based on the premise that the equation describing the system must be dimensionally homogeneous. Upon performing the necessary mathematics, the equation becomes:

$$A_{iOL} = (1/a_i^2)(L'/\mu_L a_i)^X (\rho_L^2 a_c / \mu_L^2 a_i^3)^Y \quad (69)$$

where X and Y are constants to be determined from the experimental data. Note that the dimensionless groups are simply the Reynolds number and the Grashof number, both based on the specific surface area of the packing. The data for both the Sumitomo and the wire gauze packings with the 45.72 cm diameter rotor were used to determine the values of X and Y. Again, average values of  $L'$  and  $a_c$  calculated by Equation (66) were used. The equation produced from the data is:

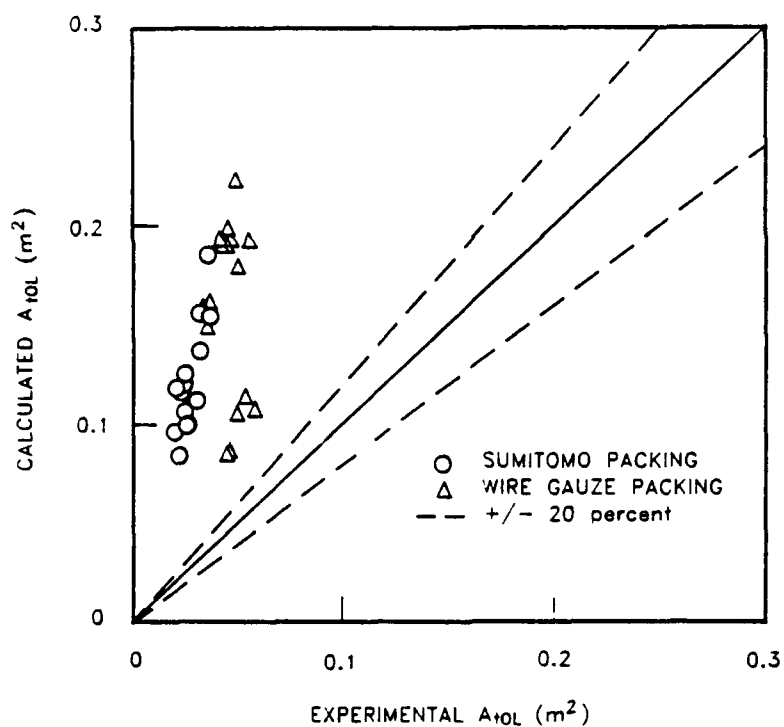


Figure 45. Comparison of the Experimental  $A_{OL}$  with that Predicted by Correlation Proposed by Vivian et al (Reference 24).

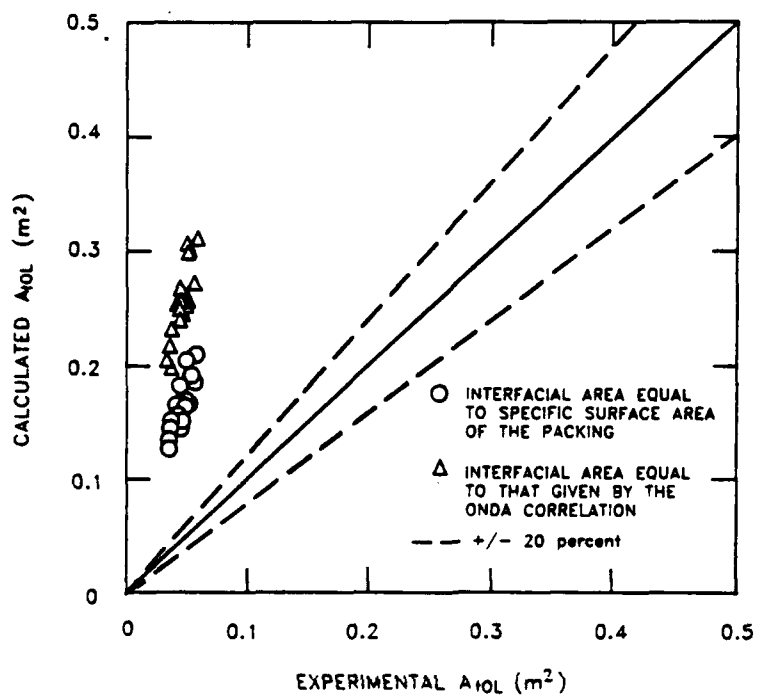


Figure 46. Comparison of the Experimental and Predicted  $A_{OL}$  for the Wire Gauze Packing.

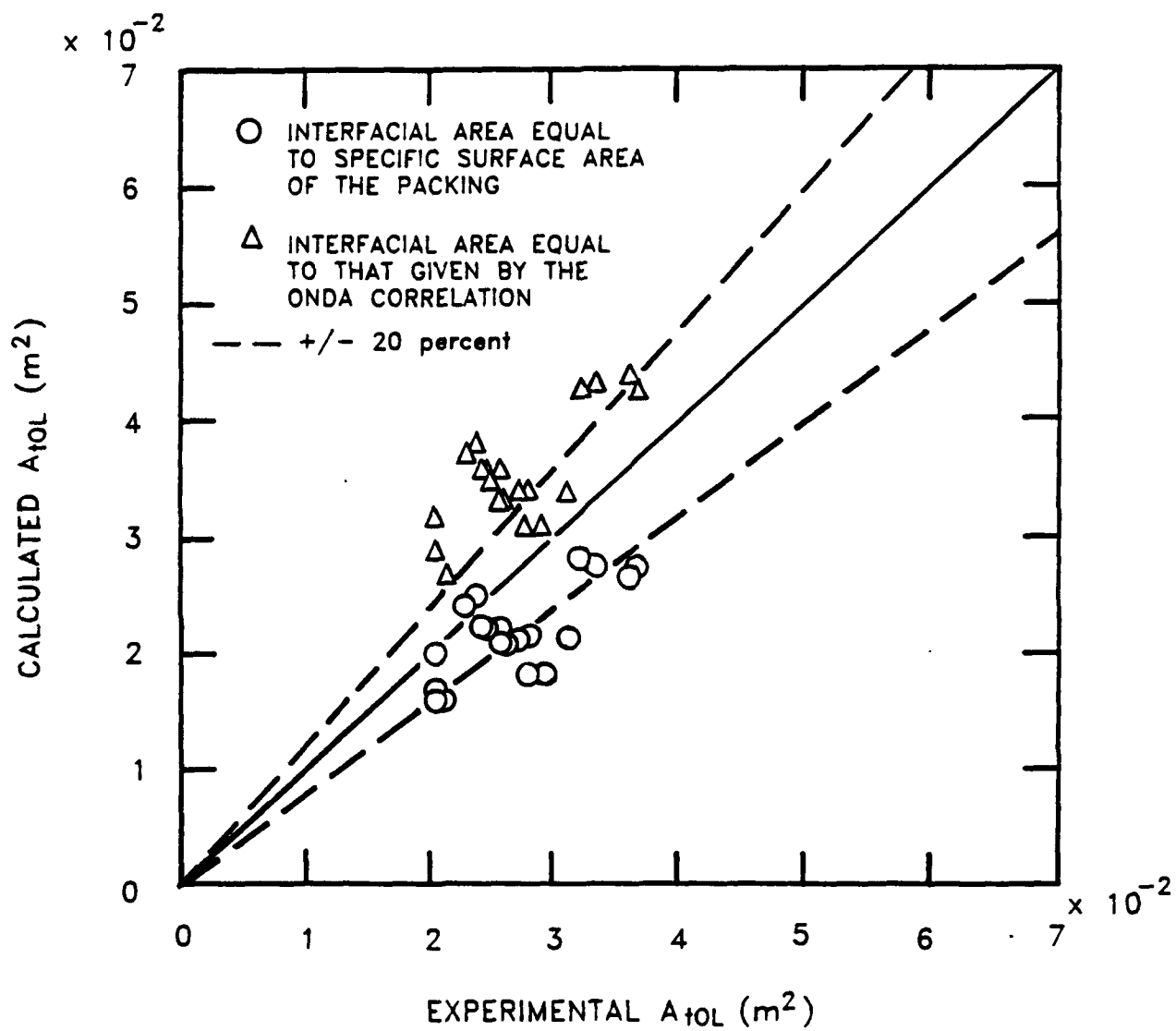


Figure 47. Comparison of the Experimental and Predicted  $A_{tOL}$  for the Sumitomo Packing.

$$A_{\text{OL}} = \frac{337,143}{a_i^2} (L' / \mu_L a_i)^{0.6} (\rho_L^2 a_c / \mu_L^2 a_i^3)^{-0.15} \quad , \quad (70)$$

where the dimensions of the variables are:  $A_{\text{OL}} = \text{m}^2$ ,  $L' = \text{kg/m}^2\text{-second}$ ,  $\rho_L = \text{kg/m}^3$ ,  $\mu_L = \text{kg/meters-second}$ ,  $a_i = \text{m}^2/\text{m}^3$ , and  $a_c = \text{meters/s}^2$ . The exponents of both the Reynolds number and Grashof number are close to those of the previous correlations. The  $A_{\text{OL}}$  calculated using this correlation is compared with the experimental data in Figure 48. Although the coefficient of determination ( $r^2$ ) from regression analysis was only 0.61, the correlation predicts the  $A_{\text{OL}}$  within plus or minus 20%, which is similar to what existing correlations predict for the conventional packed tower.

The proposed correlation has two advantages over existing correlations. First, it uses parameters which are easy to define for the centrifugal vapor-liquid contactor and no knowledge of interfacial area is needed. Second, the dependence of  $A_{\text{OL}}$  on specific surface is given more emphasis than other variables. It should be pointed out that the above correlation is based on the assumption the rate of mass transfer is liquid-film controlled. For air stripping systems, this assumption may not be unreasonable since diffusivities in the gas phase are four orders of magnitude higher than in the liquid phase. The proposed correlation could be made more general by including the Schmidt number. However, since the Schmidt number in the experimental data remained constant at approximately 1400, it was not included.

## 2. Hydraulic Results and Discussion

### a. General Characteristics

The effects of gas flow rate and rotor speed on pressure drop with no aqueous flow are shown in Figure 49. As would be expected, the pressure drop increased with an increase in both the air flow rate and rotor speed. Notice that even with no gas flowing through the packing, there was a measurable pressure drop across the packing. This pressure drop was due to the packing torus acting as a centrifugal pump. The leveling out of the curves at rotational speeds less than 200 rpm for the higher gas flows resulted from inleakage of water, which was used to lubricate the seal, into the center of the packing torus.

A typical family of pressure drop curves with both the liquid and gas phases flowing is shown in Figure 50. Like the pressure drop behavior with no liquid flow, the pressure drop initially decreased with a decrease in rotational speed. After some critical rotor speed was reached, the pressure drop began to increase very rapidly. The rotor speed at which the pressure drop began to

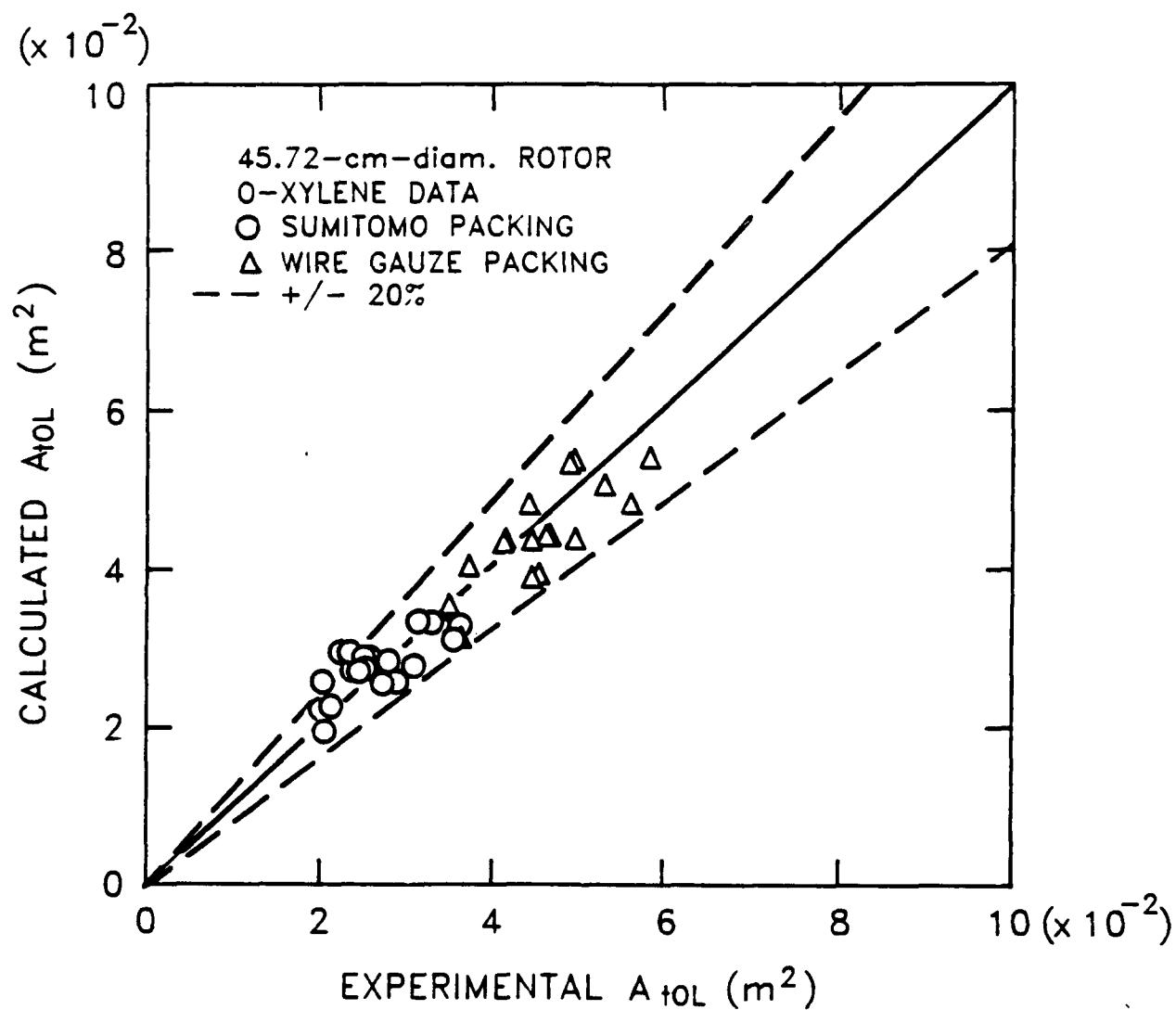


Figure 48. Comparison of the Experimental and Calculated  $A_{tOL}$  Using Correlation Based on the Specific Surface Area of Packing.

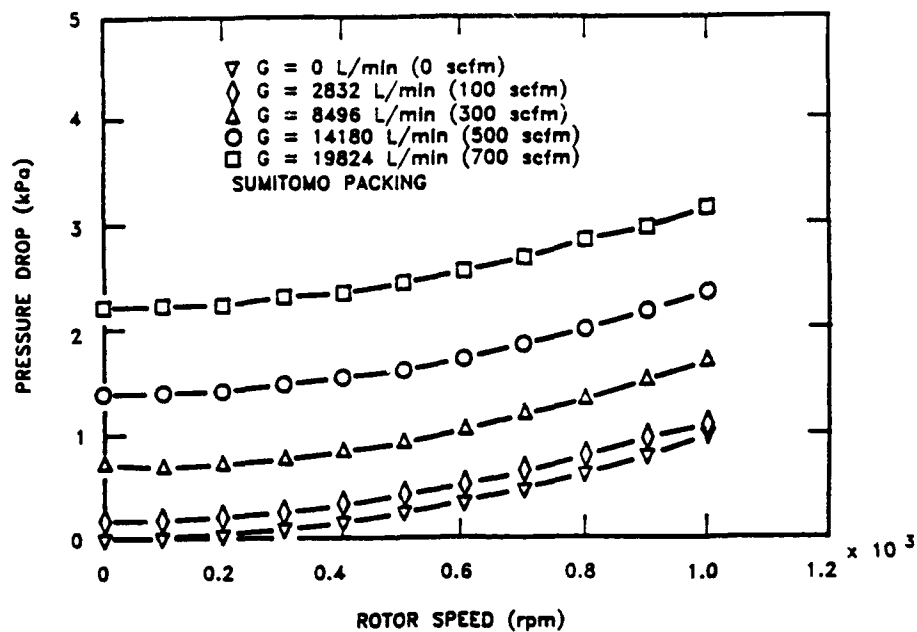


Figure 49. Pressure Drop as a Function of Rotor Speed Without Liquid Flow (76.20 cm Diameter Rotor).

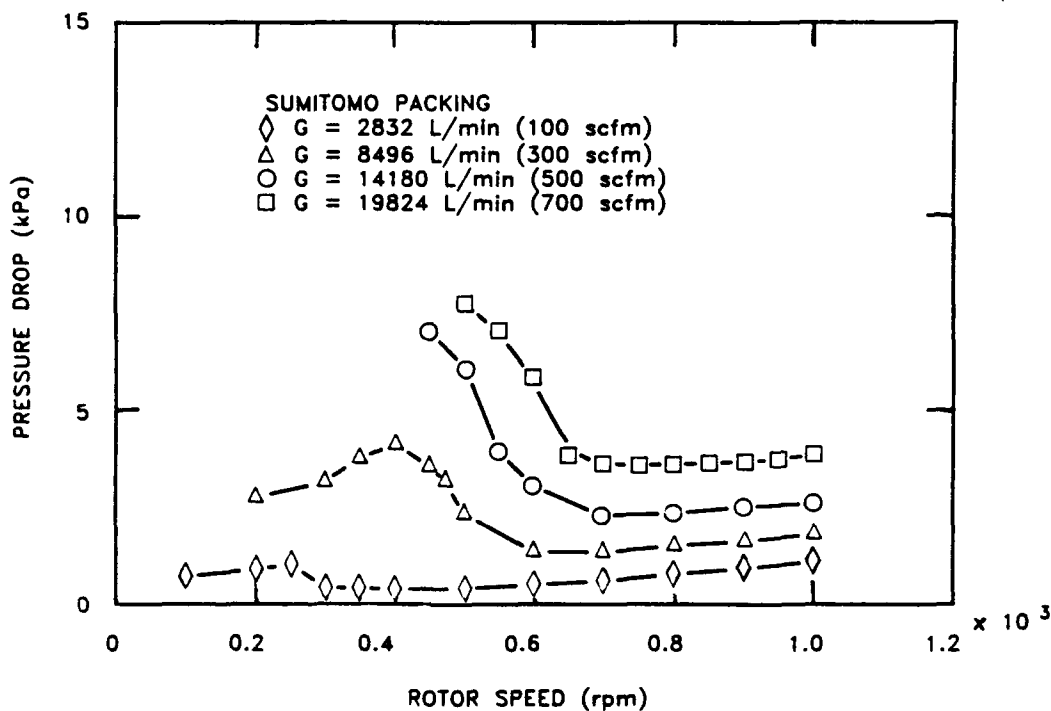


Figure 50. Pressure Drop with Both Liquid and Gas Phases Flowing (Liquid Flow Rate is 0.63 Liters/Second; 76.20 cm Diameter Rotor).



increase is a point on the lower boundary in Figure 50. This demarcation was very sharp, with changes in rotation speeds of less than 25 rpm resulting in large pressure changes. The rise in pressure drop can be caused by either the failure of the water to enter the packing, or the lack of sufficient centrifugal force to drive the water through the packing once it enters the packing. Because the hydraulic tests were performed with the top of the unit removed, visual inspection of the inner eye of the packing torus indicated that the initial increase in pressure drop as rotor speed was decreased resulted from a lack of sufficient centrifugal force. Although some mist was noticed in the exit air stream when the pressure drop first started to increase, the eye of the packing torus did not begin to fill up until the rotor speed was further reduced by almost 200 rpm. Another observation which tended to support the insufficient centrifugal force hypothesis was the slow increase in pressure drop reading with time at a constant rotation speed in the critical region, indicating buildup of liquid in the packing.

The second decrease in pressure drop at low gas flows in Figure 50 resulted from a phenomenon where the liquid phase flowed through the lower section of the packing and the gas phase flowed through the top section. This type of flow pattern resulted because the water leaving the distributor simply hit the packing and ran downward rather than being accelerated into the packing. This phenomenon was not noticed at the higher gas flows because the gas velocity through the packing was too high to permit the countercurrent flow of the aqueous phase.

The effect of packing depth (outer radius minus inner radius) on pressure drop is shown in Figure 51. An anomaly is seen in this data. The data from the 60.96 cm diameter rotor (17.8 cm packing depth) showed considerably higher pressure drops than would be expected from examining the data from the two other rotors. Since a logical explanation for this behavior was not readily apparent, the fabrication and assembly processes of the three rotors were examined. Glitsch, Inc., indicated that Sumitomo packing used in the 76.20 cm diameter rotor (25.4 cm packing depth) was new, while the packing used for the other two rotors had been previously used in a unit to selectively remove  $H_2S$  from natural gas. Since the  $H_2S$  removal is a clean process, the packing should not have been plugged with deposits. However, the pressure drop for the 60.96 cm diameter rotor was higher than what would be expected from Glitsch's data with other units. Consequently, the data from the 60.96 cm diameter rotor were used only for analysis of end effects in the mass transfer tests and for determining power consumption requirements.

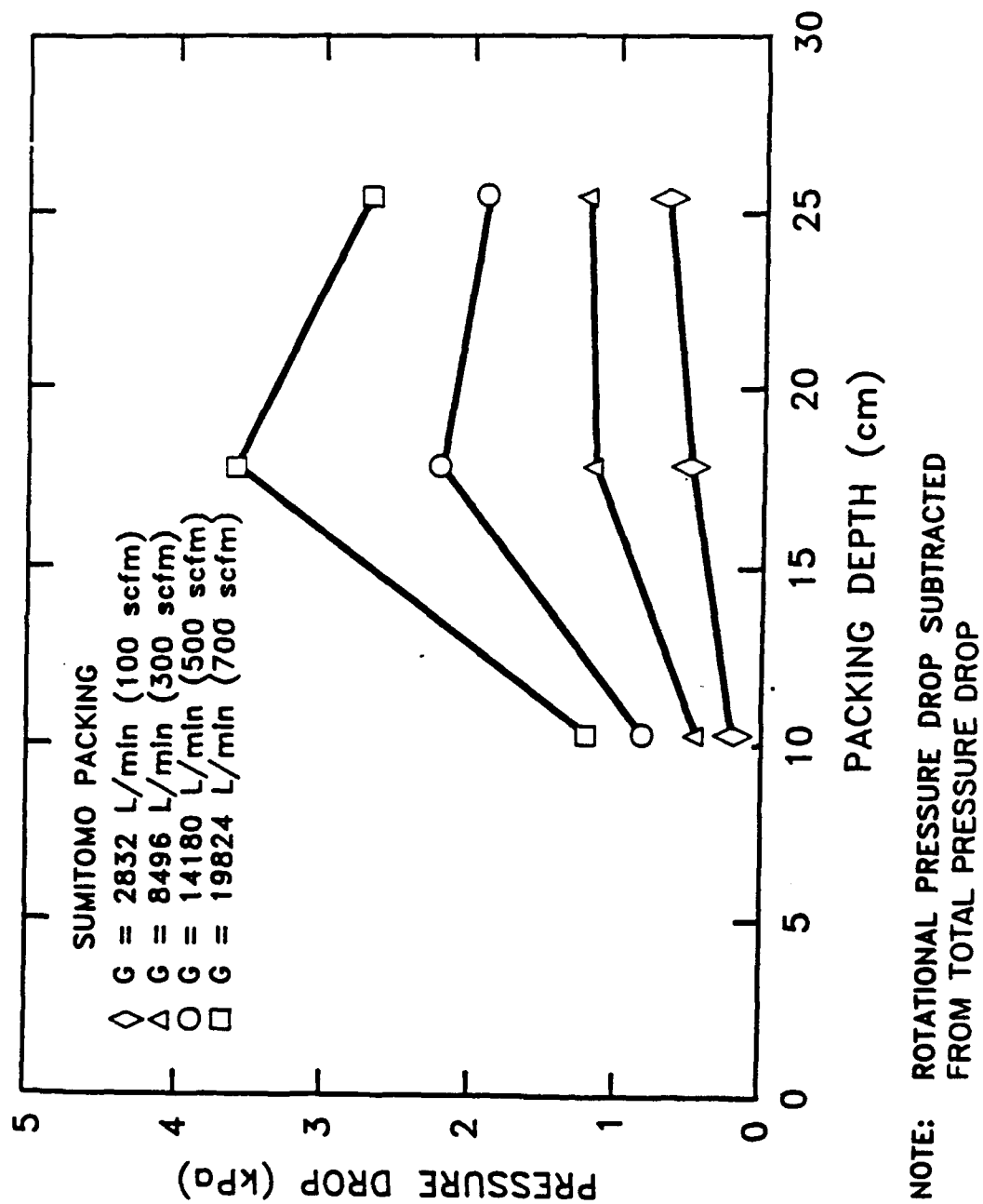


Figure 51. Effect of Packing Depth on Pressure Drop (Liquid Flow Rate = 0 Liters/second; Rotor Speed = 700 rpm).

### **b. Hydraulic Capacity Correlation**

The onset of flooding or limit of operability in conventional packed columns may be defined as a region of operating conditions where countercurrent flow of the two phases is disturbed and pressure drop across the column begins to oscillate. Although not totally applicable to the centrifugal vapor-liquid contactor, this definition can be useful in characterizing hydraulic performance. Unlike conventional packed towers in which flooding is achieved by increasing gas and liquid flows, flooding in a centrifugal vapor-liquid contactor can be initiated at constant fluid flows by decreasing the rotational speed of the packing torus. This approach was utilized in developing a hydraulic capacity correlation.

The Sherwood flooding correlation for conventional packed towers has been recommended by several authors (References 23 and 27) for designing a centrifugal vapor-liquid contactor. Thus, it would be beneficial to compare data from this study with the Sherwood flooding correlation. To perform this comparison, a quantitative definition of what constitutes the limit of operability was established. Examination of the hydraulic data from all the runs indicated that, as rotational speed was initially decreased, the pressure drop decreased at a rate of approximately 24.9 Pa/100 rpm. After some critical operating speed was reached, the pressure drop began to increase at a rate of 498 Pa/100 rpm or higher. This was a significant rise in pressure drop, indicating that something in the operating characteristics had changed. The limit of operability for the rotational speed was thus defined as the speed below which the pressure drop increased at a rate that is greater than or equal to 498 Pa/100 rpm. For example, if at certain operating conditions a decrease in speed from 500 to 400 rpm resulted in pressure drop increase of 498 Pa/100 rpm, then 500 rpm was taken as the limit of operability for the rotational speed. Although the choice of 498 Pa/100 rpm was somewhat arbitrary, it provided a quantitative definition which was convenient to use. Tests with the 76.20 cm diameter rotor at 9.4 liters/second did not exhibit a sharp increase in pressure drop, and the limit of operability for the rotational speed was assumed to be the speed below which no further decrease in pressure drop occurred.

The results of the hydraulic capacity tests are shown in Figure 52, along with the Sherwood correlation. These results indicate that the Sherwood correlation underestimated the limit of operability for the rotational speed in the case of the Sumitomo packing. However, there was good agreement for the wire gauze packing. A second order polynomial curve fit for the experimental data is also shown in Figure 52. The equation of this curve is:

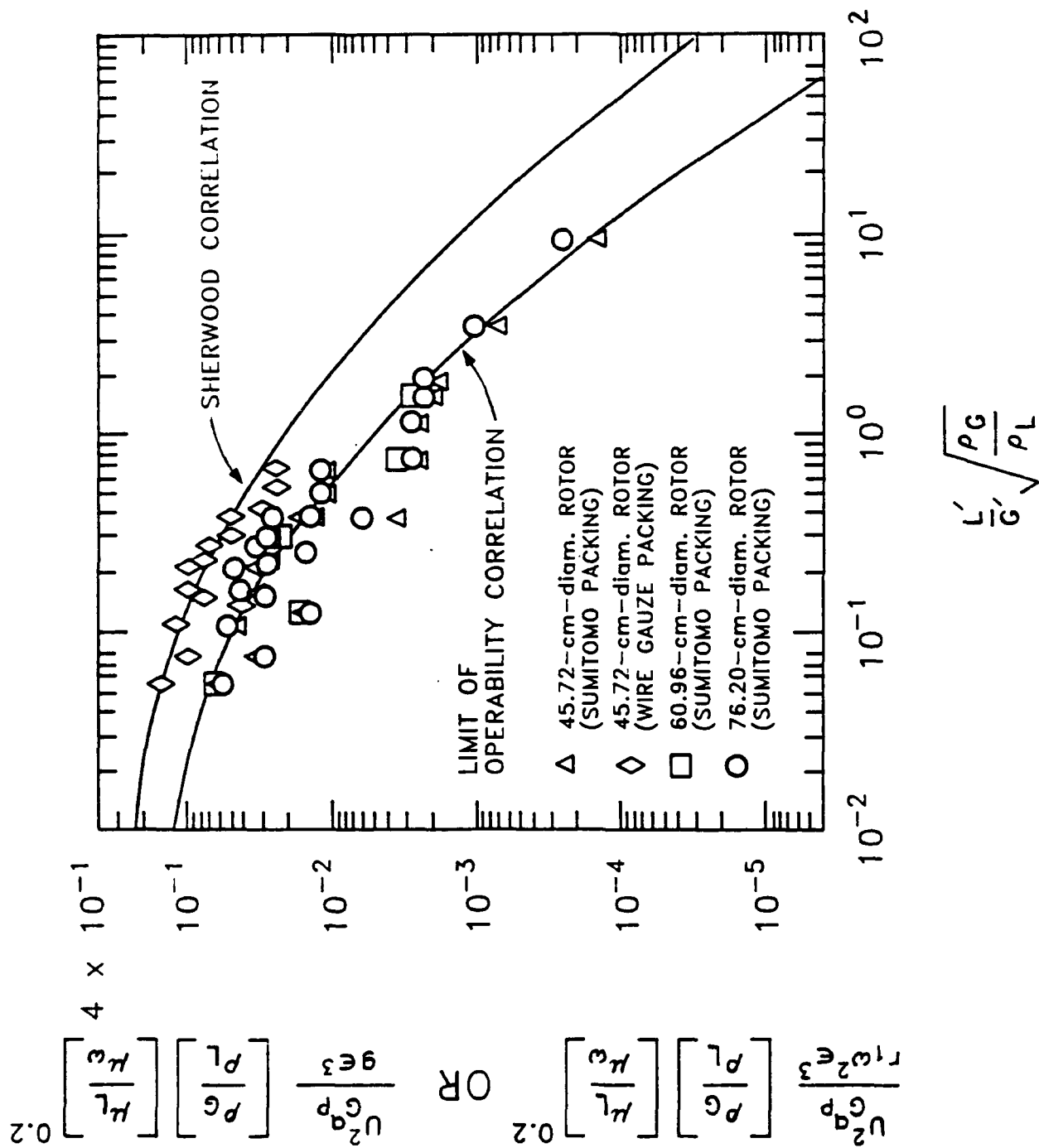


Figure 52. Comparison of Limit of Operability Data With That Predicted by the Sherwood Flooding Correlation.

$$\log y = -2.274484 - 1.1367 \log(x) - 0.168118 [\log(x)]^2 \quad (71)$$

where  $x$  and  $y$  are the values of the abscissa and ordinate, respectively. The coefficient of determination ( $r^2$ ) for the equation was 0.80. From Figure 52, it is interesting to note that, although the 60.96 cm diameter rotor exhibited unusually high pressure drop, the limits of operability for the rotational speed are identical to those of the other two rotors.

### c. Pressure Drop Correlation

As discussed earlier, the pressure drop across the rotating packing torus of a centrifugal vapor-liquid contactor is difficult to model theoretically. Thus, a semi-theoretical approach based on experimental observation was used. The pressure drop across the packing can be divided into two terms. The first term accounts for the pressure drop due to rotation of the packing, and the second term accounts for pressure drop resulting from the flow of fluids through a porous media.

The effects of superficial gas and liquid velocities on pressure drop, in the region where rotational speed is greater than the limit of operability for the rotational speed, are shown in Figures 53 and 54, respectively.

As can be seen from Figure 55, the effect of liquid flow rate on pressure drop was relatively minor and can be neglected. The nonlinearity of the data in Figure 53 indicated that the inertial term [(second term, in Equation (52))] is the dominant term for the experimental conditions. Thus, as a further simplification, the first term in Equation (52) can be neglected.

The effect of packing depth on pressure drop for the 45.72 and the 76.20 cm diameter rotors is shown in Figure 55. This figure shows that, under the experimental conditions, the assumption that pressure drop varies linearly with packing depth is valid. Thus, the pressure drop due to the flow of gas through the packing can be written as:

$$\Delta P_{flow} = \beta \rho_{av} (r_2 - r_1) V_{av}^2 \quad (72)$$

The value of  $\beta$  can be estimated using the Ergun equation (Reference 40). The Ergun equation, however, uses the concept of mean particle diameter to define  $\beta$ . The particle diameter is difficult to estimate for the type of packings used in the centrifugal vapor-liquid contactors. It would be more convenient to express  $\beta$  in terms of the specific surface area of the packing. Since  $\beta$  is simply an empirical constant, Equation (72) can be modified to give:

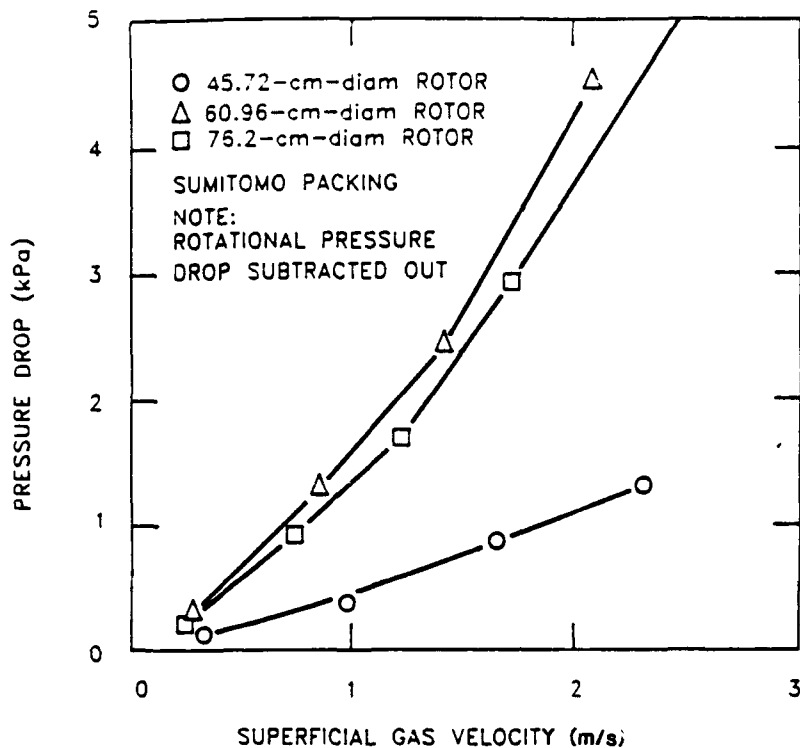


Figure 53. Effect of Gas Flow Rate on Pressure Drop (Liquid Flow Rate = 0.63 Liters/Second).

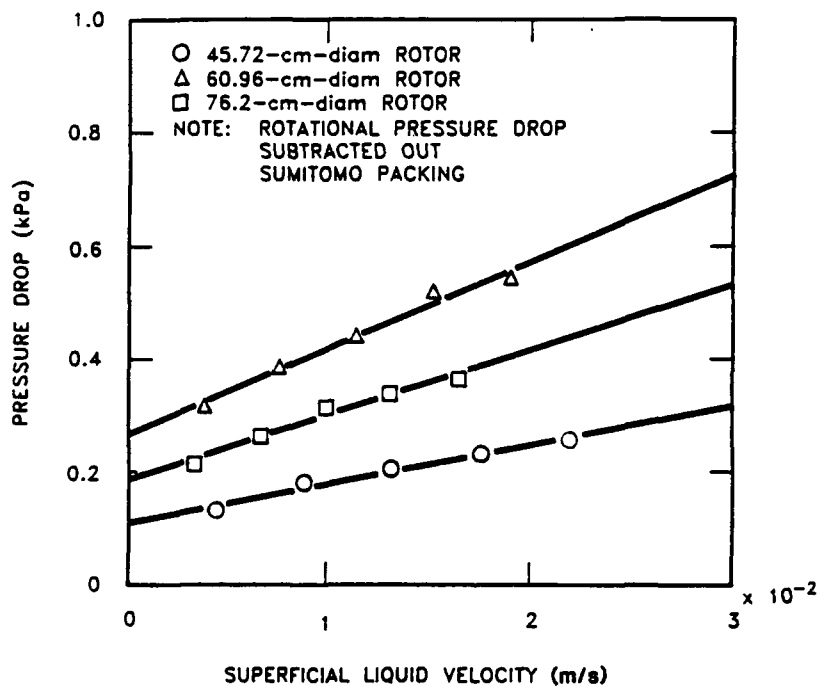


Figure 54. Effect of Liquid Flow Rate on Pressure Drop (Gas Flow Rate = 47.2 Liters/Second).

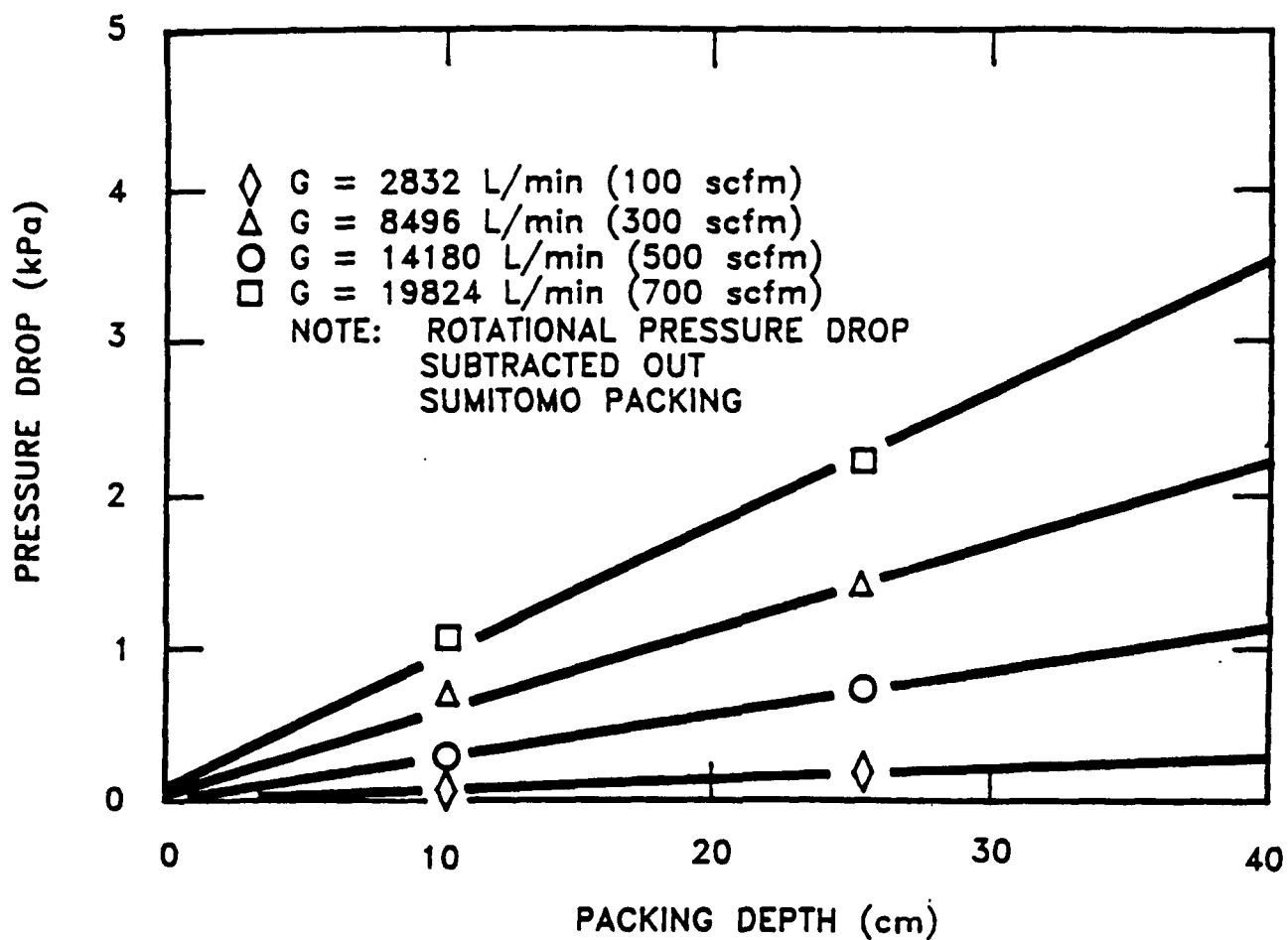


Figure 55. Effect of Packing Depth on Pressure Drop at Several Gas Flow Rates (Liquid Flow Rate = 0; Rotor Speed = 700 rpm).

$$\Delta P_{flow} = \beta_1 \frac{a_t}{\epsilon} \rho_{air} (r_2 - r_1) V_{avg}^2, \quad (73)$$

where  $a_t$  is the specific surface area of packing and  $\epsilon$  is the voidage of the packing material. Combining Equations (52) and (73) for calculation of total pressure drop gives:

$$\Delta P_{tot} = A \frac{\rho_{air} \omega^2}{2} (r_2^2 - r_1^2) + \beta_1 \left( \frac{a_t}{\epsilon} \right) \rho_{air} (r_2 - r_1) V_{avg}^2. \quad (74)$$

The constants  $A$  and  $\beta_1$  can be evaluated from the experimental data using regression analysis. The pressure drop data from the 45.92 cm diameter and 76.20 cm diameter rotors, for rotational speeds greater than the limit of operability for the rotational speed, give the following equation:

$$\Delta P_{tot} = 0.923 \rho_{air} \omega^2 (r_2^2 - r_1^2) + 0.992 \frac{a_t}{\epsilon} \rho_{air} (r_2 - r_1) V_{avg}^2, \quad (75)$$

where the dimensions of the variables are:  $\Delta P_{tot}$  = pascals,  $\rho_{air}$  = kg/m<sup>3</sup>,  $r$  = meters,  $a_p$  = m<sup>2</sup>/m<sup>3</sup>,  $\omega$  = rad/second, and  $V$  = meters/second. The coefficient of determination ( $r^2$ ) for the regression fit is 0.94. The calculated and experimental pressure drop values are compared in Figure 56. Although the approach outlined above is a rather simple representation of a complicated system, it does a reasonable job in describing the experimental data and is convenient to use.

#### d. Power Consumption

The power consumed by the centrifugal stripper at various operating conditions was measured in order to determine the contribution from each variable. Since the power meter was located before the variable frequency drive, the measured power consumption includes losses due to inefficiencies in the frequency drive and the motor. There was no attempt made to separate these losses.



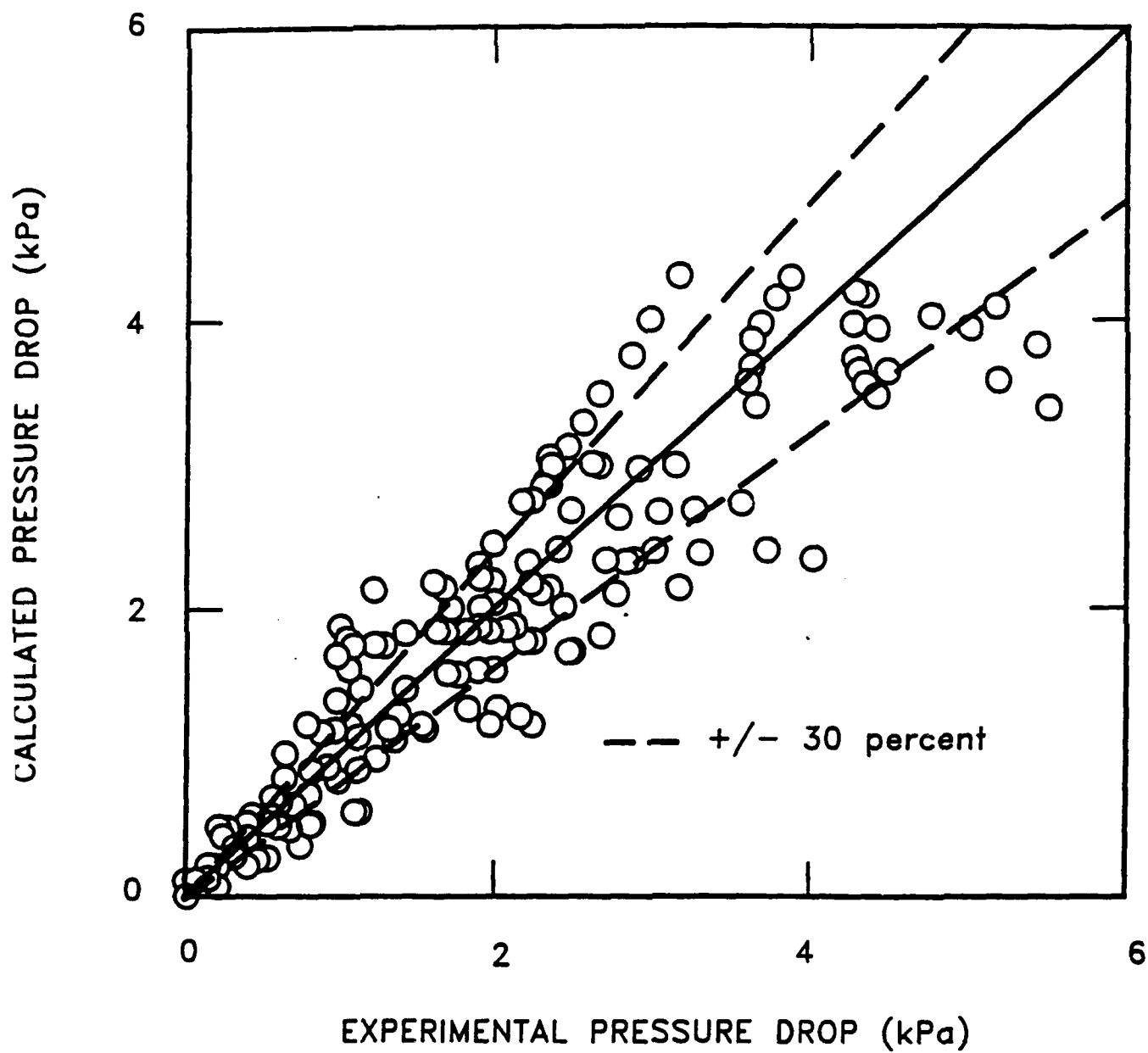


Figure 56. Comparison of the Calculated and Experimental Pressure Drop.

The effect of gas flow rate on the power consumption is shown in Figure 57. The power consumption of the centrifugal stripper decreases slightly with an increase in gas flow rate. This reduction results from the gas transferring the energy to the rotating packing as it flows from a region of high pressure (high energy) to a region of low pressure (low energy). The effects of rotor speed and liquid flow rate on power consumption are shown in Figures 58 and 59, respectively. The quantity of power used increased with the squares of the outer rotor radius and rotor speed, and linearly with the liquid flow rate. These relationships are not totally unexpected since a similar behavior is observed in centrifugal pumps.

In Equation (54), the energy recovered from the gas phase is neglected since it is very small, and B accounts for the slippage between the packing and liquid phase that occurs as the liquid phase is being accelerated. The experimental data from all three rotors, in a region where the rotational speed was greater than its limit of operability, gave the following equation:

$$P_c = 1.222 + 0.0011\rho_L r_2^2 \omega^2 Q \quad . \quad (76)$$

The coefficient of determination ( $r^2$ ) for this equation was 0.92. The power consumption calculated using this equation is compared with the experimental data in Figure 60. The correlation does a reasonable job in describing the power consumption over the operating conditions.

#### e. General Operating Experience

One of the advantages cited in the literature of a centrifugal vapor-liquid contactor as compared to a conventional packed tower is the ability to resist fouling of the packing caused by deposition of suspended solids or precipitation of dissolved metals, such as iron and magnesium, due to oxidation. During the mass transfer tests, the center point run was used to monitor whether any change was taking place with time. These tests indicted that there was no significant change in pressure drop. During this time, hydraulic tests were also performed at 1.89 liters/second of liquid flow and 141.6 liters/second of air at regular intervals. The results of these tests for the 45.72 cm diameter rotor are shown in Figure 61. At these conditions, the packing appears to be fouling. A similar phenomenon was also observed for the 76.20 cm diameter rotor. The 60.96 cm diameter rotor, which had unusual pressure drop behavior initially, became plugged and unbalanced during continuous operation for four days at the end of the mass transfer tests.

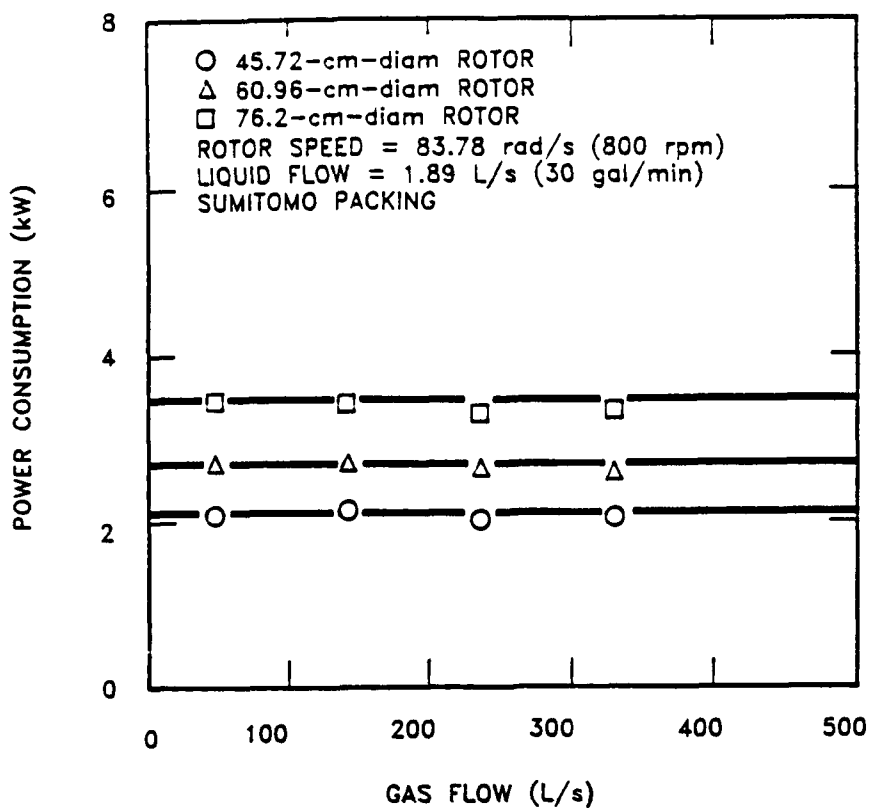


Figure 57. Effect of Gas Flow Rate on Power Consumption of the Centrifugal Stripper.

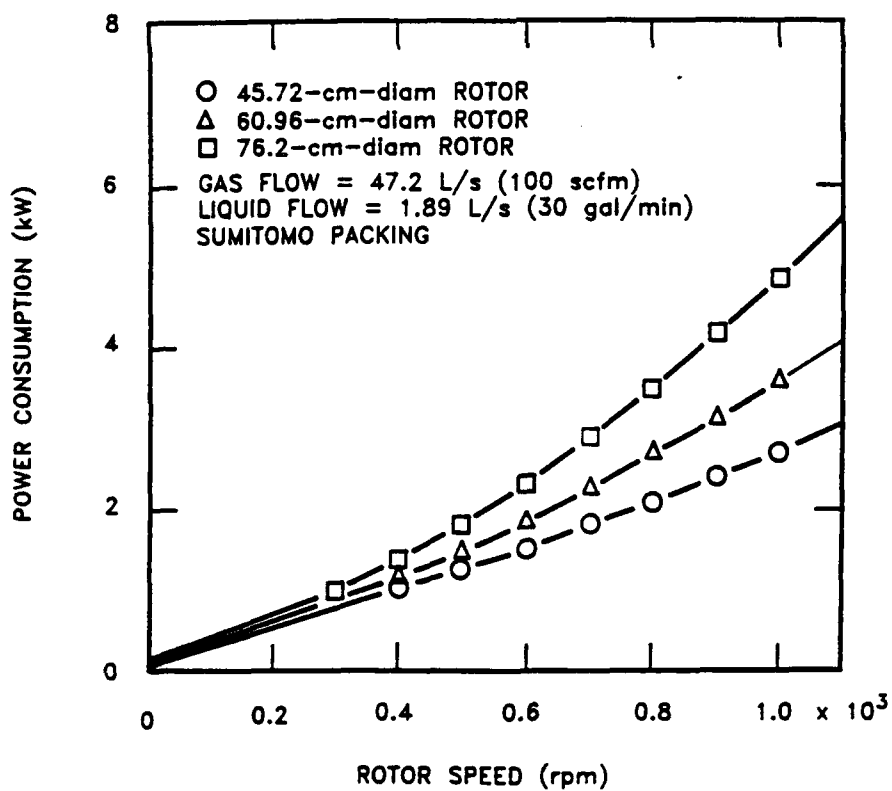


Figure 58. Effect of Rotor Speed on Power Consumption of the Centrifugal Stripper.

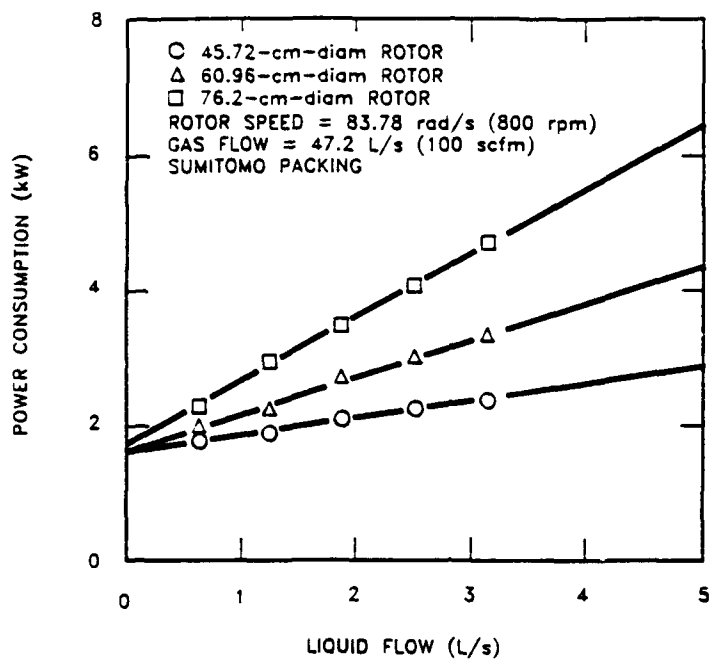


Figure 59. Effect of Liquid Flow Rate on Power Consumption of the Centrifugal Stripper.

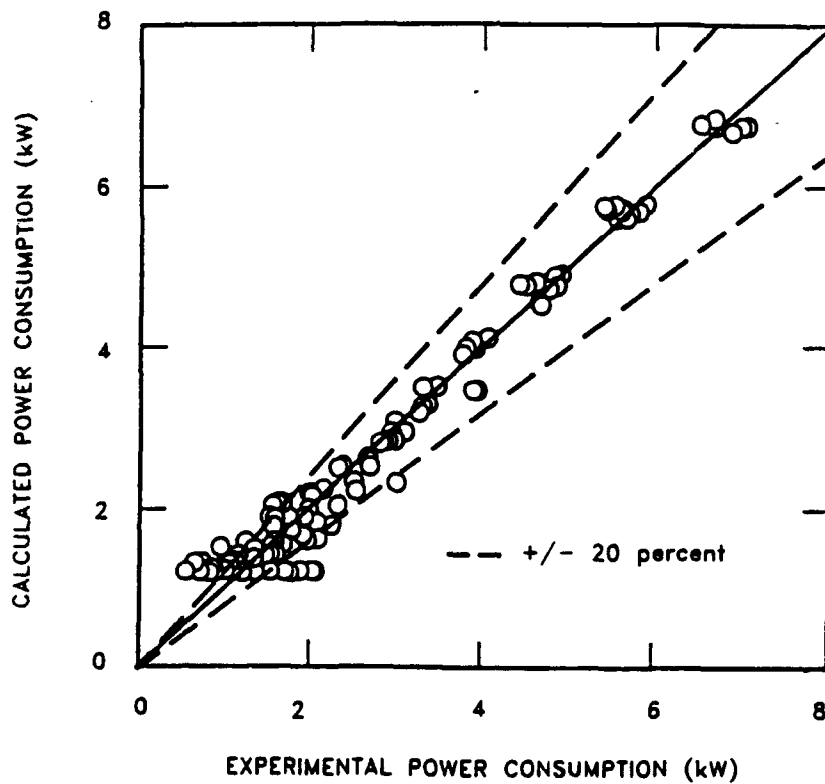


Figure 60. Comparison of the Experimental and Calculated Power Consumption of the Centrifugal Stripper.

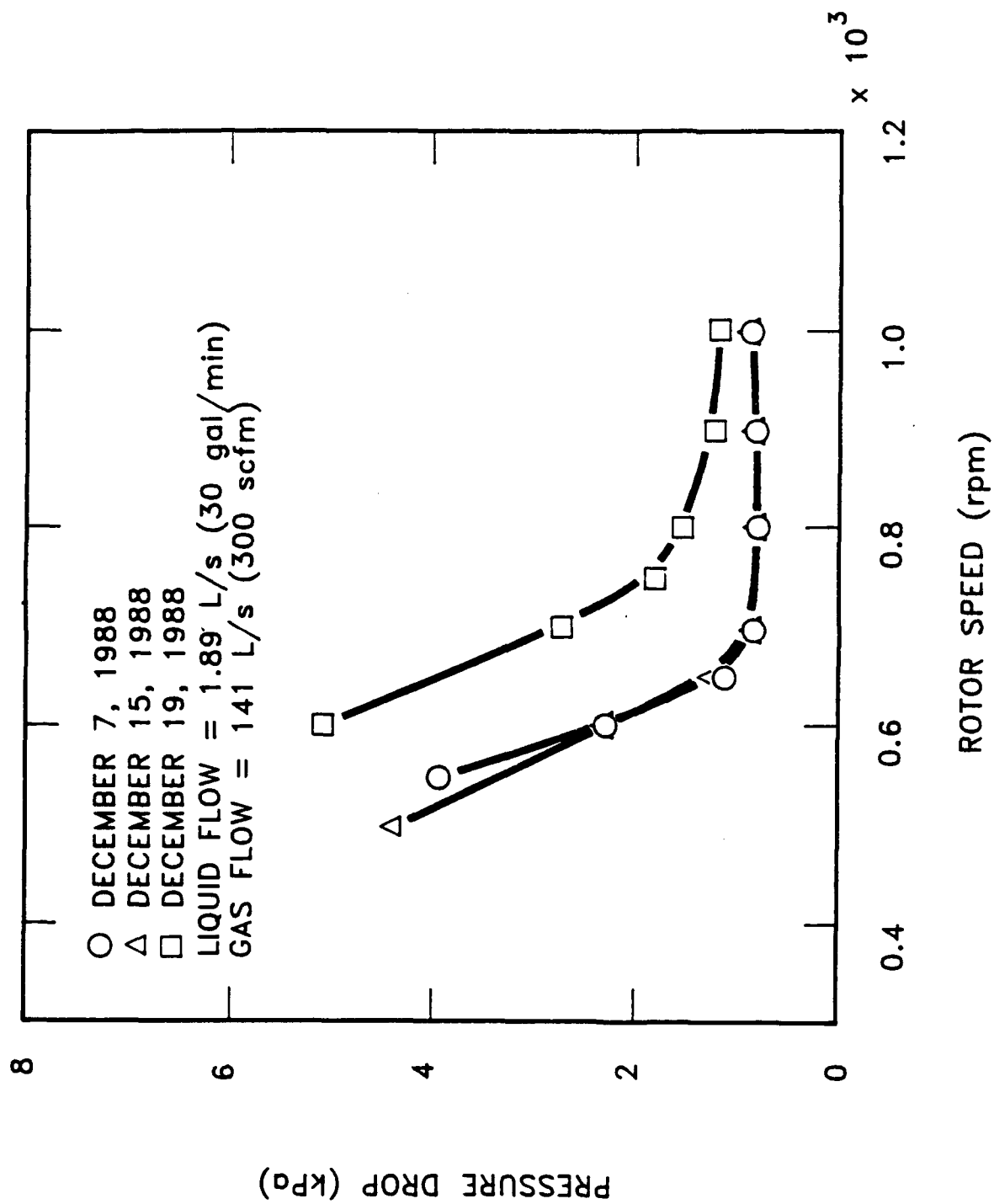


Figure 61. Rise in Pressure Drop as a Result of Fouling for the 45.72 cm Diameter Rotor.

When the Sumitomo packing was removed from the 45.72 cm diameter rotor, a considerable amount of coating on the outer layers of the packing was observed. In addition, the lower part of the rotor showed much more deposition than the upper part. There is no apparent explanation for this, other than that the packing contains a certain amount of water when the rotor is stopped and this water flows down the packing and out. This flow pattern could have deposited more minerals on the lower part of the rotor as the water evaporated. Results of chemical analysis of the solids removed from the rotor are given in Table 20. The groundwater at Eglin AFB contains a significant amount of iron (9 ppm) and this appears to be the main culprit in plugging the rotor. The Al, Cr, and Ni in the precipitate came from the packing torus, when the precipitate was removed from the rotor by scraping. The quantity of these elements in the groundwater was small.

From these observations, it appears that the shearing action is not able to scrub the packing as well as claimed previously, and that the centrifugal vapor-liquid contactor is susceptible to plugging when the mineral content of the groundwater is high. Thus, some pretreatment of the groundwater may be required. It should be pointed out that the packings used in the conventional packed tower for this project also showed a considerable deposition of minerals. Thus, plugging would be expected to occur with continued operation. Groundwater with iron content as high as encountered at Eglin AFB should be pretreated prior to any air stripping operations.

### **C. CATALYTIC DESTRUCTION TESTS**

When operation of the catalytic destruction unit was initiated, problems were encountered with establishing a constant reactor temperature. Initially, the reactor temperature was automatically controlled by adjustment of the power to the preheater. Because of the slow response time of the preheater, oscillation of the reactor temperature resulted. The control scheme was modified by changing the control point from the reactor temperature to the preheater temperature. Thus, by automatically controlling the preheater temperature, the reactor temperature could be held at a constant value. Also, the reactor temperature could be adjusted to the desired level by manually adjusted the setpoint of the preheater controller.

TABLE 20. ELEMENTAL ANALYSIS OF THE PRECIPITATE

ELEMENT	QUANTITY (mg/kg)
Ag	<8.7
Al	$2.0 \times 10^5$
As	$8.7 \times 10^1$
B	$1.7 \times 10^2$
Ba	$9.5 \times 10^1$
Be	$<7.0 \times 10^{-1}$
Ca	$1.5 \times 10^3$
Cd	<3.5
Co	$1.8 \times 10^1$
Cr	$5.9 \times 10^2$
Cu	$2.1 \times 10^2$
Fe	$1.9 \times 10^4$
Ga	$<5.2 \times 10^2$
Li	$<3.5 \times 10^2$
Mg	$1.3 \times 10^3$
Mn	$2.0 \times 10^2$
Mo	$<7.0 \times 10^1$
Na	$<8.7 \times 10^2$
Ni	$2.7 \times 10^4$
P	$9.0 \times 10^3$
Pb	$8.4 \times 10^1$
Sb	$8.5 \times 10^2$
Se	$<1.4 \times 10^2$
Si	$1.9 \times 10^3$

TABLE 20. ELEMENTAL ANALYSIS OF THE PRECIPITATE (CONCLUDED)

ELEMENT	QUANTITY (mg/kg)
Sn	$<8.7 \times 10^1$
Sr	$<8.7$
Ti	$3.6 \times 10^2$
V	$2.4 \times 10^1$
Zn	$1.6 \times 10^2$
Zr	$<3.5 \times 10^1$



With the gas sampling system described in Section IV, the catalytic unit samples had to be taken sequentially. To confirm that the operating conditions remained constant while all samples, i.e., the preheater influent, the preheater effluent, and the reactor effluent, were taken, either one or both of the preheater effluent and the reactor effluent streams were sampled again. With the control system modified as described above, the duplicate sample results demonstrated that the steady-state conditions were maintained during the time required to take and analyze the four or five gas samples (3 to 4 hours).

The catalytic destruction unit showed low efficiencies with the two Engelhard catalysts tested at all flow rate and temperature conditions. A sample of used catalyst was examined by Engelhard and found to have sulfur present on the catalytic surface. Two analyses of the groundwater (using a Hach kit) showed that the groundwater contained between 250 ppb and 750 ppb of sulfur. Although Engelhard indicated that these catalysts have exhibited some tolerance to sulfur in other services, the sulfur levels in these tests evidently were too high for the catalyst to perform effectively.

A sample of an ARI catalyst from an ARI incinerator being used for a soil venting project at Hill AFB, Utah,\* was also tested. This catalyst also produced low efficiencies. In one run, however, a set of gas samples, which was taken from the catalytic destruction unit almost immediately after introduction of the VOC-laden stripper effluent, showed a conversion efficiency of approximately 80 percent. However, a following set of gas samples, again taken almost immediately after the first set, showed a conversion efficiency of only about 10 percent. Apparently, deactivation of the catalyst by sulfur occurred very rapidly. The ARI catalyst is normally utilized in a fluidized bed rather than in a fixed-bed reactor. Supposedly, due to the continuous renewal of the surface, which is caused by the attrition resulting from the motion in the fluidized bed, the ARI catalyst is relatively resistant to poisons. Therefore, this catalyst may produce higher efficiencies if used in a fluidized bed reactor.

#### **D. ADSORPTION TEST RESULTS**

In conducting the adsorption experiments, the THA was utilized to continuously monitor the adsorption bed influent and effluent, and GC samples were taken periodically. Almost immediately after the initiation of any of the adsorption runs, the THA reading on the adsorber bed effluent was observed to be approximately 50 percent of the reading on the feed to the bed. This effect was not

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\*DePaoli, D. W., et al., "Field Demonstration of *In Situ* Soil Venting of JP-4 Jet Fuel Spill Site at Hill Air Force Base," in preparation, 1991.

seen from the GC results, as evidenced by a comparison of the total areas produced from the adsorber bed influent and effluent samples. Both the THA and GC sample lines were run together from the air stripping skid to the analytical trailer. Also, both lines were heat traced and insulated together. Thus, the THA results could not be explained by residue in the sample line, because the GC results would have been affected similarly. Apparently, there was a significant quantity of low molecular weight compounds that were not being trapped either by the adsorber bed or by the Tenax trap in the LSC 2000 purge and trap system. In order to identify these compounds on the GC, modifications would have to be made on the LSC 2000 to allow low temperature operation of the Tenax trap. Consequently, in analyzing the results of the adsorption experiments, breakthrough was defined as the time when the benzene concentration in the bed effluent began to increase significantly.

Two runs were conducted using activated carbon to remove the VOCs from the stripper exit air stream. Table 21 shows loadings at breakthrough for a run at 25 percent relative humidity. The breakthrough curves are shown in Figure 62. The loadings for the 100 percent humidity run are shown in Table 22, and the breakthrough curves in Figure 63. As expected, the relative humidity in the air stream had a strong effect on the carbon bed's capacity. The carbon had approximately twice the capacity for the jet fuel components under the 25 percent humidity conditions than at the higher humidity level. Note from Tables 21 and 22 that the weight of carbon used was different between the two runs. Although the breakthrough time shown in Figure 63 is longer than in Figure 62, the capacity was lower.

Three experiments were conducted using two different molecular sieve materials as adsorbents. Molecular sieves are aluminosilicates that have undergone heating to remove water of hydration. They possess high porosity, with pores of uniform size and essentially molecular dimensions. Molecules larger than the pore size are not adsorbed because they are physically excluded from the active site adsorption sites. The activated carbon in the steel canister was replaced with the molecular sieve material for these tests. These adsorbents were of interest because of their capability of being regenerated on-site with ozone. Run 1 was performed using molecular sieve type UOP 9102, run 2 was conducted using molecular sieve UOP 13837-53, and run 3 was performed with UOP AIR-SP-S-115. The molecular sieves were generally unsuccessful adsorbing the VOCs tested. The experimental data are summarized in Tables 23, 24, and 25. Figures 64, 65, and 66 show the breakthrough curves for these runs. The poor performance of the molecular sieves may have been due, in the case of runs 1 and 2, to having too small a pore size to allow the VOC molecules access to the active adsorption sites; for run 3, the bed depth may have been insufficient.

TABLE 21. LOADINGS AT BREAKTHROUGH FOR CARBON AT LOW HUMIDITY

COMPOUND	BREAKTHROUGH
	TOTAL kg/kg CARBON
Benzene	0.007
Methyl Cyclohexane	0.043
Toluene	0.004
Meta-Xylene	0.078
Ortho-Xylene	0.018
Trimethylbenzene	0.045
Naphthalene	0.001

NOTE: 10 cfm, 25% Humidity, 2.6 lbs Carbon

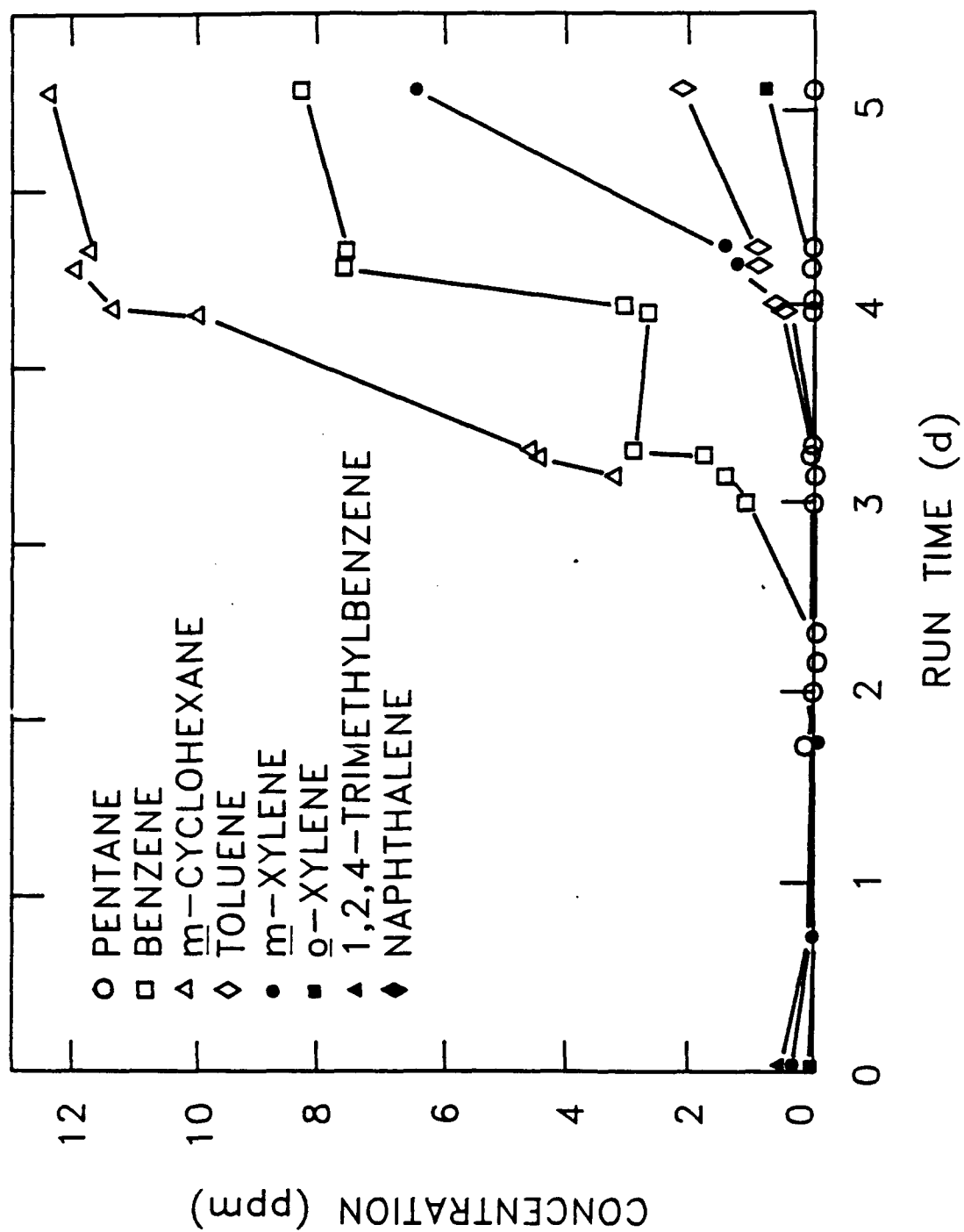


Figure 62. Results from Adsorption Tests with Activated Carbon at Low Humidity.

TABLE 22. LOADINGS AT BREAKTHROUGH FOR CARBON AT HIGH HUMIDITY

COMPOUND	BREAKTHROUGH
	TOTAL kg/kg CARBON
Benzene	0.005
Methyl Cyclohexane	0.016
Toluene	0.002
Meta-Xylene	0.029
Ortho-Xylene	0.008
Trimethylbenzene	0.017
Naphthalene	0.009

NOTE: 10 cfm, 100% Humidity, 10 lbs Carbon

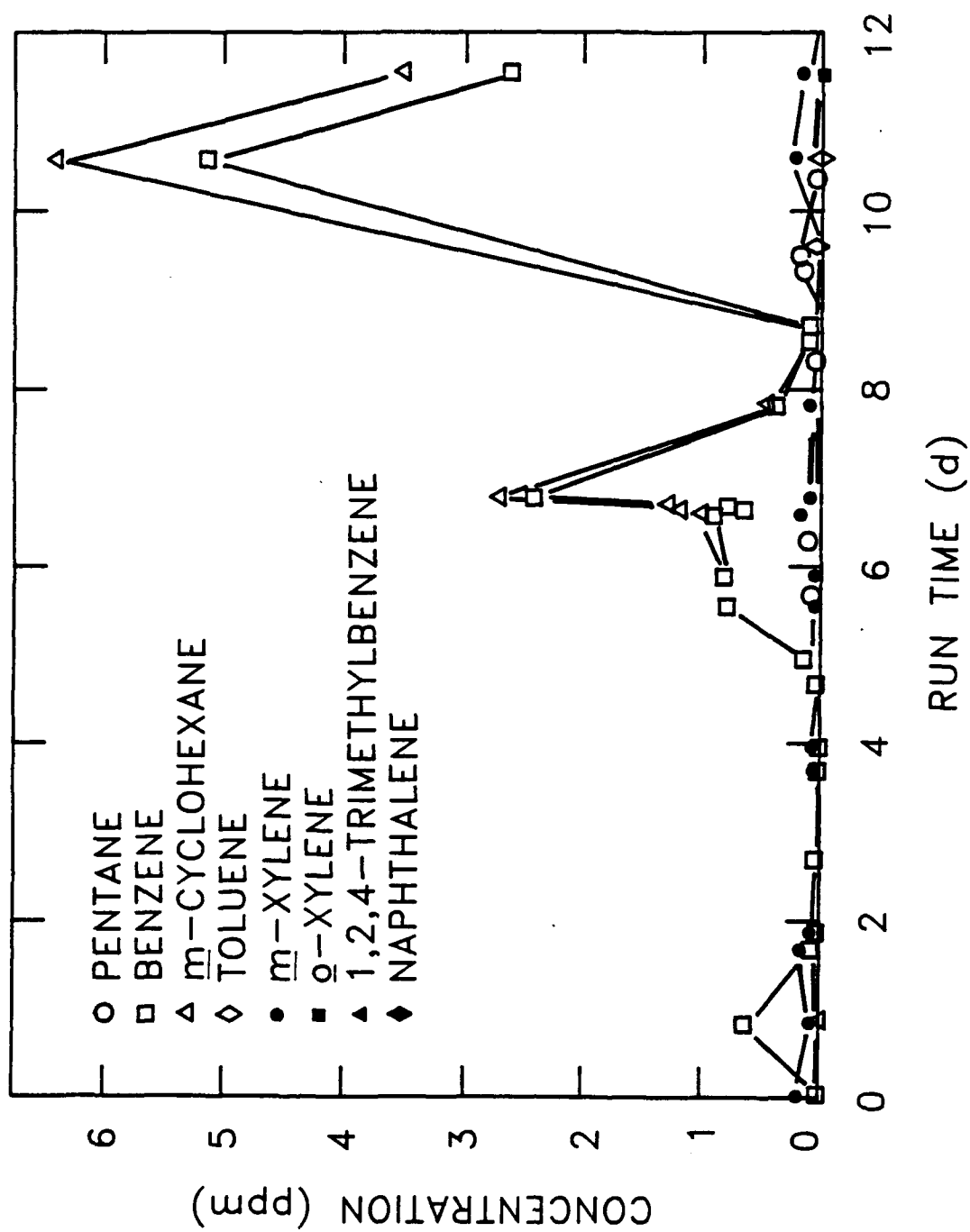


Figure 63. Results from Adsorption Tests with Activated Carbon at High Humidity.

TABLE 23. DATA FROM MOLECULAR SIEVE RUN 1

Date	Time	Run Time Min.	Run Time Days	Concentration in ppm					
				Pentane	Benzene	Methyl-Cyclohexane	Toluene	Meta-Xylene	
05/11/89	09:30	0	0.00						
05/11/89	14:09	279	0.19	1.826	2.006	4.824	0.623	2.433	
05/12/89	10:18	1488	1.03	1.81	1.888	6.265	1.059	13.867	
05/12/89	11:15	1545	1.07	1.318	1.406	4.425	0.664	4.885	
05/12/89	12:18	1608	1.12	1.651	1.795	6.203	0.924	7.319	
05/17/89	14:24	1854	1.29	1.593	1.731	5.329	0.963	10.43	
05/17/89	15:20	1910	1.33	1.551	1.812	5.436	1.023	12.093	
05/18/89	08:55	2965	2.06	1.659	1.865	7.78	1.886	31.395	
05/18/89	09:52	3022	2.10	1.514	1.728	5.445	1.066	11.532	
05/18/89	10:50	3080	2.14	1.534	1.644	5.584	1.256	21.202	
05/18/89	13:22	3232	2.24	1.53	1.758	6.051	1.289	18.073	
05/18/89	16:12	3402	2.36	1.614	1.723	5.582	1.169	16.682	
05/19/89	10:51	4521	3.14	1.528	3.90	5.623	1.115	12.113	
05/19/89	12:21	4611	3.20	1.521	1.764	5.554	1.089	11.31	
05/19/89	15:14	4784	3.32	1.64	3.753	5.483	1.065	10.663	
05/19/89	16:10	4840	3.36	1.276	2.198	4.684	0.911	8.648	

TABLE 23. DATA FROM MOLECULAR SIEVE RUN 1 (CONCLUDED)

Date	Time	Run Time Min.	Run Time Days	Concentration in ppm		
				Ortho-Xylene	1,2,4-Trimethylbenzene	Naphthalene
05/11/89	09:30	0	0.00			
05/11/89	14:09	279	0.19	0.293	0.095	0.009
05/12/89	10:18	1488	1.03	2.339	8.303	0.273
05/12/89	11:15	1545	1.07	0.653	0.377	0.007
05/12/89	12:18	1608	1.12	0.993	0.645	0.003
05/17/89	14:24	1854	1.29	1.381	0.849	0.002
05/17/89	15:20	1910	1.33	1.82	7.464	0.265
05/18/89	08:55	2965	2.06	5.048	13.125	0.009
05/18/89	09:52	3022	2.10	1.737	6.819	0.245
05/18/89	10:50	3080	2.14	3.48	9.913	0.018
05/18/89	13:22	3232	2.24	3.024	9.775	0.018
05/18/89	16:12	3402	2.36	2.868	10.885	0.016
05/19/89	10:51	4521	3.14	2.03	10.143	0.01
05/19/89	12:21	4611	3.20	1.809	6.34	0.081
05/19/89	15:14	4784	3.32	1.608	7.577	0.012
05/19/89	16:10	4840	3.36	1.412	6.254	0.009



TABLE 24. DATA FROM MOLECULAR SIEVE RUN 2

Date	Time	Run Time Min.	Run Time Days	Concentration in ppm				
				Pentane	Benzene	Methylcyclohexane	Toluene	Metaxylene
05/23/89	08:50	0	0.00					
05/23/89	13:22	272	0.19	0.011	0.011	1.779	0.261	9.704
05/23/89	15:23	393	0.27	0.031	0.103	1.996	0.251	9.385
05/23/89	16:19	449	0.31	0.038	0.126	2.04	0.247	9.221
05/24/89	08:24	1432	0.99	0.748	1.199	3.172	0.291	8.747
05/24/89	10:54	1564	1.09	1.65	4.045	6.104	0.426	14.533
05/24/89	14:36	1786	1.24	1.214	1.761	3.502	0.353	8.749
05/24/89	15:34	1844	1.28	1.194	1.674	3.534	0.347	8.336
05/25/89	08:16	2846	1.98	2.081	2.263	4.492	0.605	8.933
05/25/89	09:12	2902	2.02	1.753	1.886	6.494	1.347	12.91

TABLE 24. DATA FROM MOLECULAR SIEVE RUN 2 (CONCLUDED)

Date	Time	Run Time Min.	Run Time Days	Concentration in ppm		
				Orthoxylene	1,2,3-Trimethylbenzene	Naphthalene
05/23/89	08:50	0	0.00			
05/23/89	13:22	272	0.19	2.785	7.727	0.056
05/23/89	15:23	393	0.27	2.711	7.472	0.073
05/23/89	16:19	449	0.31	2.658	7.239	0.072
05/24/89	08:42	1432	0.99	2.506	6.639	0.321
05/24/89	10:54	1564	1.09	2.979	7.536	0.296
05/24/89	14:36	1786	1.24	2.674	6.506	0.092
05/24/89	15:34	1844	1.28	2.555	6.157	0.29
05/25/89	08:16	2846	1.98	2.64	6.091	0.265
05/25/89	09:12	2902	2.02	2.79	6.294	0.24

TABLE 25. DATA FROM MOLECULAR SIEVE RUN 3

Date	Time	Run Time Min.	Run Time Days	Concentration in ppm				
				Pentane	Benzene	Methylcyclohexane	Toluene	Metaxylene
05/27/89	10:48	0	0.00	1.426	1.874	5.527	1.237	14.722
05/27/89	10:55	0	0.00					
05/27/89	11:53	58	0.04	0.054	0.167	0.494	0.225	6.567
05/27/89	14:09	194	0.13	0.395	0.176	0.644	0.233	8.734
05/28/89	10:48	1433	1.00	1.098	1.354	1.639	0.348	9.24
05/28/89	11:45	1490	1.03	1.501	1.778	5.763	1.245	14.071
05/29/89	10:48	2873	2.00	1.473	1.673	2.856	0.607	7.392
05/29/89	11:45	2930	2.03	1.482	1.589	5.699	1.071	10.297
05/30/89	09:12	4217	2.93	1.633	1.622	3.922	0.799	7.631
05/30/89	10:09	4274	2.97	1.53	1.443	5.833	0.966	8.908

TABLE 25. DATA FROM MOLECULAR SIEVE RUN 3 (CONCLUDED)

Date	Time	Run Time Min.	Run Time Days	Concentration in ppm		
				Orthylene	1,2,4-Trimethylbenzene	Naphthalene
05/27/89	10:48	0	0.00	2.669	7.724	0.283
05/27/89	10:55	0	0.00			
05/27/89	11:53	58	0.04	1.354	5.252	0.014
05/27/89	14:09	194	0.13	2.094	7.211	0.043
05/28/89	10:48	1433	1.00	2.453	7.334	0.079
05/28/89	11:45	1490	1.03	2.664	7.838	0.073
05/29/89	10:48	2873	2.00	2.216	5.031	0.324
05/29/89	11:45	2930	2.03	2.386	5.382	0.299
05/30/89	09:12	4217	2.93	2.089	4.67	0.318
05/30/89	10:09	4274	2.97	2.111	4.535	0.259

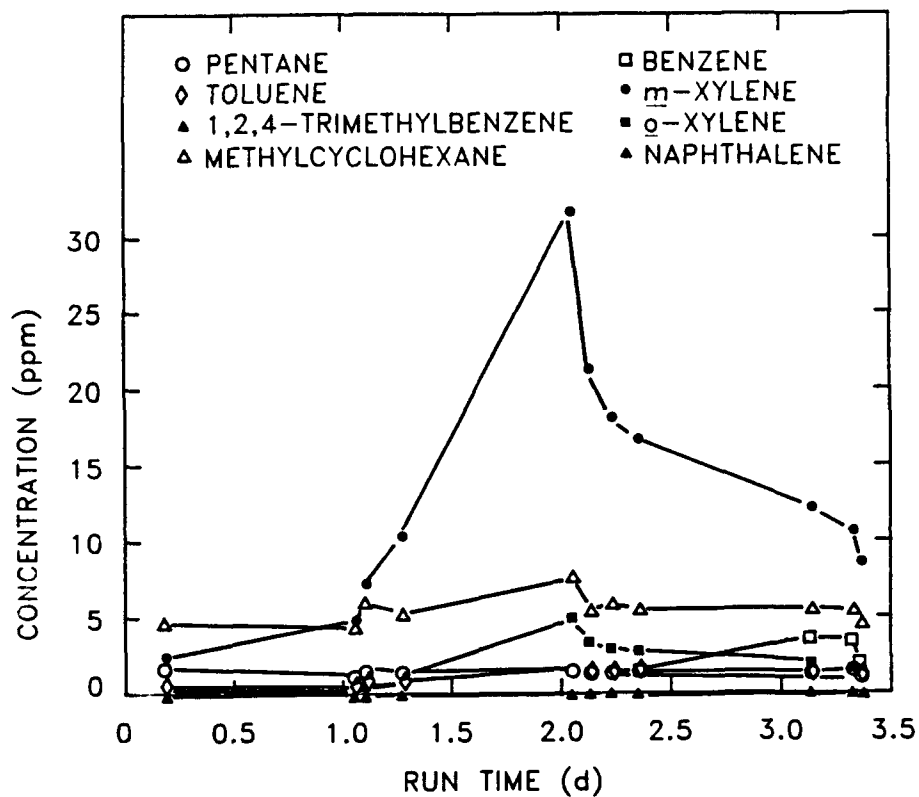


Figure 64. Results from Run 1 of Adsorption Test with Molecular Sieve Material at High Humidity.

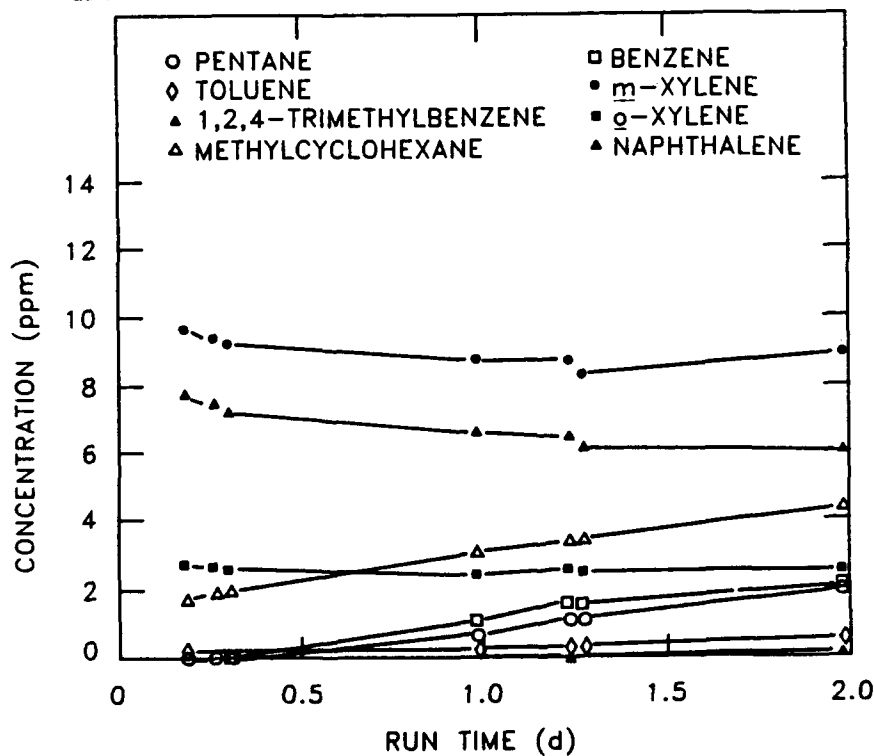


Figure 65. Results from Run 2 of Adsorption Tests with Molecular Sieve Material at High Humidity.

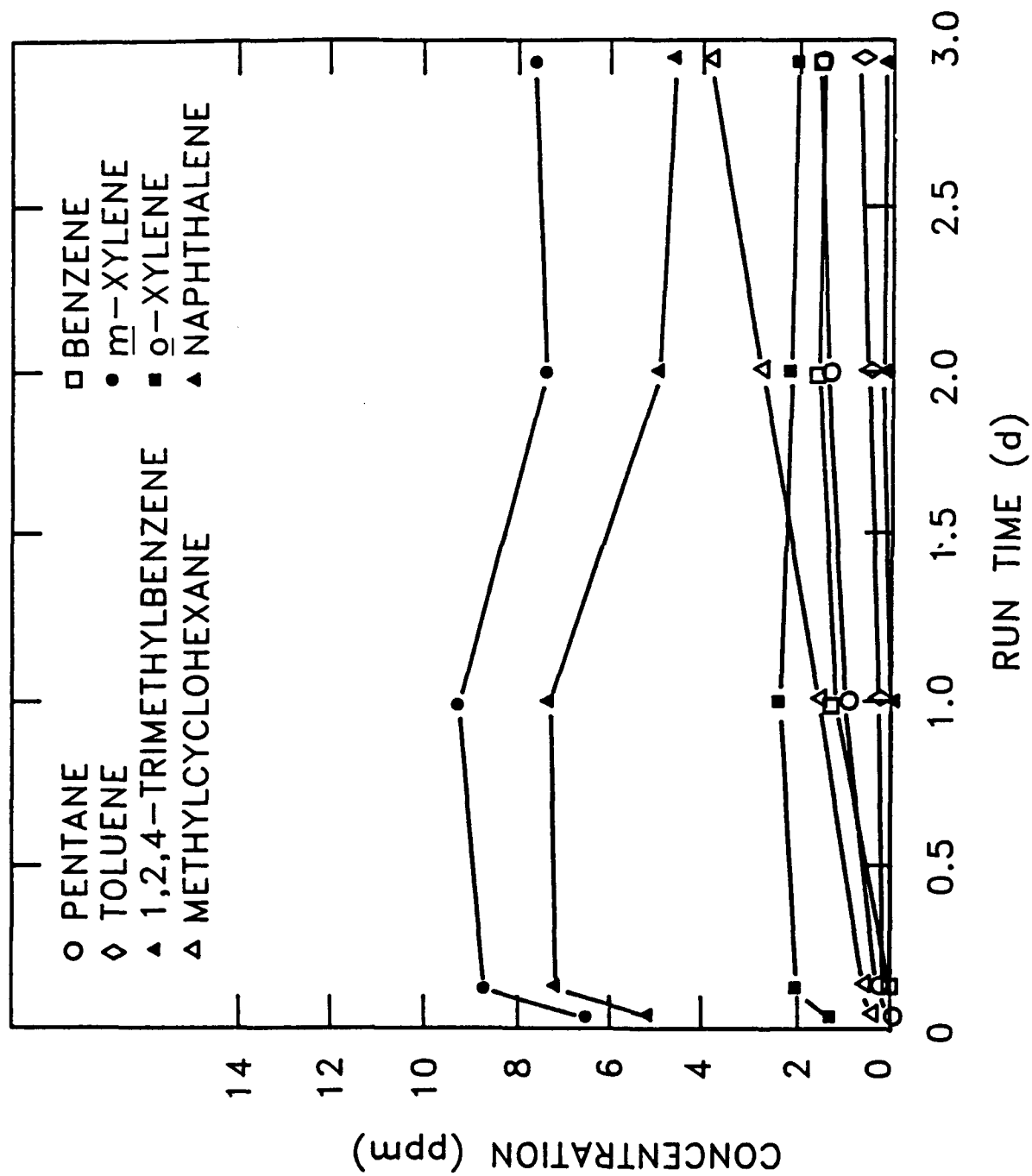


Figure 66. Results from Run 3 of Adsorption Test with Molecular Sieve Material at Low Humidity.

## SECTION VII

### ECONOMIC ANALYSIS AND EVALUATION

#### A. INTRODUCTION

This chapter presents economic evaluations of various configurations and operating conditions for full-scale groundwater cleanup equipment systems. An editorial decision was made to include a rather broad range of the data and analyses in this chapter, since useful insights into project economics arise from them. This approach was chosen even though the range of analyses now included is larger than originally specified. The eventual "standard" selected for use in this evaluation is the dollar cost per 1000 gallons of groundwater processed, over a 20 year equipment operating lifetime. This standard is a cost evaluation parameter found in other reports (References 41 and 42). The commonly accepted probable accuracy of cost estimating as carried out in this study is plus or minus 30 percent (References 43, 44, and 45). Trend analyses and functional relationships amongst variables can, however, be evaluated at a far higher level of precision, and thus data tables and graphs used here are based upon five significant figures or better.

#### B. EQUIPMENT SYSTEMS

The components of the groundwater cleanup systems consisted of:

- A packed column stripper or a centrifugal stripper. Included with this unit are the pumps and piping involved with wells to provide access to the groundwater,
- A carbon adsorption system for cleanup of off-gas from the stripper,
- Or, as an alternative, a catalytic incineration system for cleanup of off-gas from the stripper.

Thus, six equipment configurations are possible and are treated in the economic studies. Other key technical design parameters used for the economic studies are summarized as follows:

- Stainless steel construction for the stripper, the submerged pump for the groundwater system, but not for any other unit operations.
- Plastic Flexiring® packing
- Oil fired preheating of off-gas entering the carbon adsorption system, to reduce relative humidity and improve adsorption.
- Oil fired heating of catalytic incineration unit.

Other input parameters are identified in Table 26 of this chapter.

TABLE 26. DESIGN INPUT VARIABLES FOR SPREADSHEET (TABLE 1 OF SPREADSHEET SIMULATION)

DESIGN INPUT TABLE (Base Case Independent Design Variable Inputs)			
General Inputs, Units	Value	Efficiencies	Value
Operating temperature, Fahrenheit	60	Air Heaters	0.7
Inlet Gas Pressure, Atmospheres	1.00	Air Blowers	0.6
Groundwater Stream		Water Pumps	0.7
Water Feed Rate, Gallons/Minute	500	Stripper Related Parameters	
Contaminant Concentration, ppb IN	10000	Groundwater Depth, ft	30
Contaminant Cleanup Factor	0.990	Fanning Friction Factor	0.008
Stripper Tower		Horizontal Pipe Length, ft	100
Stripping Factor	4.0	Consolidated Friction Loss Coefficient for valves, elbows, etc.	15
Packing Information		Carbon Air Stream Cleanup	
Packing Size, mm (in)	50(2)	Carbon Recycle Interval, days	7
Packing Factor	20	Carbon Use Safety Factor	1.5
Correlation Factor Term*	1.502	Carbon Bulk Density, lb/ft <sup>3</sup>	30
Flooding Factor	0.4	Catalytic Incineration Air Stream Cleanup	
Height of Each Packed Bed, ft	10	Catalytic Unit Size Safety Factor	1.5



TABLE 26. DESIGN INPUT VARIABLES FOR SPREADSHEET (TABLE 1 OF SPREADSHEET SIMULATION) (CONCLUDED)

<b>OVERALL OPERATING CYCLE LOAD FACTOR</b> (365 days/year = 1.00)	0.85
<b>COST PARAMETERS</b>	
Equipment Installation Factor (Stripper)	2.20
EIF (Carbon and Catalytic)	1.60
Materials (SS) Factor, STRIPPER	1.70
Fuel Oil, 1990 \$/MMBTU	6.15
Electricity Cost, 1990 \$/kwh	0.060
Operations & Maintenance Factor	0.150
Overhead Rate (%) on Expense	100
Average Annual Inflation: 1977-90	0.0484

Some special variations in the base case parameters are identified as part of the subsequent data analyses.

\*Treybal (1980).

Preliminary specifications for this economic study were to omit consideration of catalytic incineration for off-gases containing TCE. There are two technical reasons for this decision: first, some catalysts may be vulnerable to halogen poisoning, and second, there remains an environmental issue as to the form in which the chlorine leaves a catalytic incineration unit.

For completeness of economic evaluation, catalytic incineration of TCE in the stripper off-gas has been included, but one must continue to recognize a need for attention to technical considerations.

### **C. CONTAMINANT SYSTEMS**

The groundwater contaminants for the purpose of this evaluation are jet fuel and trichloroethylene (TCE). The cost of cleanup of water contaminated with jet fuel may be estimated using the concentration of benzene in the groundwater and accounting for the presence of other components where necessary.

### **D. COMPUTER PROGRAMS**

Economic analysis and evaluation described here utilizes Microsoft MULTIPLAN spreadsheet software. Other spreadsheet software is, of course, available. The MULTIPLAN spreadsheet, however, has at least two important advantages for the current application.

- Mathematical iterations can be carried out readily, without the need for macro routines.
- Range names without subscripts can be used for mathematical calculations.

All programs used for the current project were written in Multiplan Version 2.01. This may be exported upward without difficulty into Version 3.0 or 4.0. Three spreadsheet files (two copies each) were developed to support economic evaluation studies.

#### **1. VOC-2100**

This is a dual purpose spreadsheet, which generates those design parameters necessary for estimation of fixed capital and of annual expense (noncapital) costs. The design information is then carried over into estimation (in 1990 dollars) of the fixed capital and the annual expense items. Freundlich Equation coefficients were estimated using the SPEQ.FOR program developed by R. D. Cortright of Michigan Tech University. Some experimental carbon adsorption data were provided from the current experimental activities. A government-owned (break even, or zero profit) scenario is stipulated. Thus, there is no consideration of the time phasing between expense and revenue, and working capital need not be included in the cost estimations. A list of independent

variables from VOC-2.100 is provided in Table 26. A complete set of the 26 tables of VOC-2.100 is provided as Appendix A. The cost estimation methods are covered in detail by Counce et al.\*

## **2. VOC-2.200**

Late in the project a decision was made to evaluate an alternative method of cost estimating summarized in work done for the EPA (Reference 45). In order to retain future flexibility of choice, the spreadsheet was modified into a second file, VOC-2.200 rather than to discard/replace the VOC-2.100 file. The changes were fairly minor so that VOC-2.200 is not presented in the appendix.

## **3. VOC-2.300**

Outputs from the two alternative design and cost estimating spreadsheets outlined above are used for lifetime (20 year) financial evaluation. This is done with spreadsheet file VOC-2.300. Input data for VOC-2.300 are provided here as Tables 27 and 28. A complete set of illustrative tables from VOC-2.300 is provided as Appendix B to this report.

## **E. COST ESTIMATION METHODS**

Details of the cost estimation methods are found in a "user manual"\* being prepared as a supplement to this report. The cost estimation methods evolved over the life of the project into four general categories as outlined below.

- Method A - This method makes use of original cost-estimating methods summarized by Counce et al.\*

(A-1) - Concentrations of benzene and of TCE in the groundwater are both 10 ppm; for benzene, other typical jet fuel components are assumed to be present.

(A-2) - The concentration of benzene in the groundwater is 0.1 ppm; other typical jet fuel components are assumed to be present.

- Method B - This method makes use of cost estimating methods as summarized in an EPA-sponsored study (Reference 45).

(B-1) - Concentration of TCE in the groundwater is 10 ppm.

(B-2) - Concentration of benzene in the groundwater is 0.1 ppm.; other typical jet fuel components are assumed to be present.

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\*R. M. Counce et al., "Manual for Estimating Cost of VOC Removal from Groundwater Contaminated with Jet Fuel," ESL TR 90-50, Air Force Civil Engineering Support Agency, Tyndall AFB, Florida, in preparation, 1991.

**TABLE 27. INITIAL COST ESTIMATES AND OTHER KEY PARAMETERS FOR  
SPREADSHEET SIMULATION**

<b>INPUT ITEM</b>	<b>INPUT VALUE</b>
Base Year	1990
Currency Units (1E+3, 1E+6, etc.)	1.0E+06
Number of Construction Years to Startup	0
Initial Fixed Capital Contingency Add-On Adjustment	0.632401 0.00
Initial Fixed Capital, Plus Contingency	0.632401
Initial Working Capital Contingency Add-On Adjustment	0.000000 0.00
Initial Working Capital, Plus Contingency	0.000000
Initial Annual Expense Contingency Add-On Adjustment	0.581721 0
Initial Annual Expense, Plus Contingency	0.581721
First Year FC Input Fraction	1.00
Second Year FC Input Fraction	0.00
Third Year FC Input Fraction	0.00
Fourth Year FC Input Fraction	0.00
Fifth Year FC Input Fraction	0.00
Debt Fraction (Max = 1.000)	1.000
Annual Inflation During Construction	0.0484
Real Interest During Construction	0.0500
Interest During Construction	0.0984

TABLE 28. INPUT TABLE FOR PROJECT LIFETIME COST ANALYSIS

INPUT TABLE FOR OPERATING YEARS, STARTING 1990	
INPUT ITEM	INPUT VALUE
Number of Operating Years	20
Fixed Capital Cost Estimate at Startup	0.632401
Salvage Fraction	0.00
Salvage Amount	0.000000
Working Capital Factor	0.00
Initial Year Working Capital Cost Estimate	0.000000
Non-Capital Expense Factor	0.000
Initial Year Non-Capital Expense Estimate	0.581721
Operating Years Debt Fraction	1.000
Inflation Rate During Operations	0.0484
Real Interest Rate During Operations	0.0500
Interest Rate During Operations	0.0984
Tax Rate in Profits	0.00
Production Factors: L = 1.00 for 365 days per year	
First Year Factor	0.85
Second Year Factor	0.85
Third Year Factor	0.85
Fourth Year Factor	0.85
Groundwater Pumping Rate, gal/min	500
Water Annual Processing (for L = 1) in gallons/year	2.628E+08
Number of Depreciation Years (Straight Line Method)	20

An organizational chart of the data analysis runs of this report is found at Table C.1 of Appendix C, and also in the separately provided set of wide carriage computer printout data.

The analytical results and comments of the following section deal with data in each of the above four primary groupings, as well as comparisons among the groupings.

## **F. ANALYTICAL RESULTS AND CONCLUSIONS**

The evaluation "standard" used in this chapter is the operating lifetime dollar cost per 1000 gallons of groundwater processed.

### **1. Procedures**

For Method-A the VOC-2.100 design spreadsheet was used. For Method-B, the VOC-2.200 design spreadsheet was used. The base case values are those shown in Table 26 of this chapter. A few special exceptions to those base case values are noted in the following analysis subsections.

Any one of the input variables of Table 26 may be considered as a range variable, with all other inputs constant. The spreadsheet iterates through the full range of the specified variable, and generates spreadsheet tables D1B-D7B for benzene, and spreadsheet tables D1T-D7T for TCE. D6B and D6T summarize data for a packed stripper system, and tables D7B and D7T summarize data for a centrifugal stripper system. Optionally, iterations may be suppressed to yield cost estimates for a single set of input values. Refer to Appendix A for printouts of these spreadsheet tables.

The resulting outputs provide the ranges of fixed capital cost estimates, and of annual expense (non capital) cost estimates, for all values of the single range variable - with all other base case values constant. In effect, a single variable sensitivity analysis is generated by the spreadsheet.

For reasons already specified, no estimate of working capital is required. All cost estimates generated by the design spreadsheets (VOC-2.100 or VOC-2.200) are in 1990 dollars.

For operating lifetime financial analyses, the above output values of fixed capital costs and of annual expense are used as inputs to spreadsheet VOC-2.300. That operating lifetime analysis spreadsheet provides the dollar cost per 1000 gallons of groundwater processed:

- arising from the fixed capital investment,
- arising from the annual noncapital expense, and
- the composite total processing cost.

The composite total processing cost is shown as the ordinate on the following graphs, and is tabulated in Appendix C. An annual inflation adjustment is included for the annual expense category.

## **2. Method-A Results**

### **a. Group-I, A-1**

Tables 29 and 30 present data for the dollar costs per 1000 gallons of groundwater processed, in a tabular form where the water flow rate is the sensitivity variable. All other parameters are the base case values of Tables 26 and 27. The operating lifetime analyses were done using VOC-2.300. The data are from sets S.1, which utilizes a traditional packed tower, and S.2, which utilizes a rotary air stripper (see Tables C.1, C.2, and C.3 of Appendix C).

For Tables 29 and 30, a breakout of the cost contribution from the fixed capital cost, from the annual expense, and the composite total, is given. Three cases are presented: a stripper alone, stripper plus carbon adsorption treatment of the off gas, and stripper plus catalytic incineration of the off gas. The two alternatives of a packed column stripper and a centrifugal stripper also are presented. It is evident that the operating cost per 1000 gallons of groundwater processed is strongly dominated by the annual expense (non-capital) costs, and that the fixed capital costs are a much smaller component of the total. While the exact ratio between the fixed capital and the annual expense contributions varies with the specific operating conditions, the qualitative relationship shown in Tables 29 and 30 holds for all cases examined in this report. Since no exceptions were encountered, all subsequent data analyses present only the total dollar processing cost per 1000 gallons of groundwater, without any further breakout of the fixed capital and the annual expense components. A significant point must, however, be made relative to evaluation of competing alternatives for the various groundwater cleanup options, as well as generally for environmental control and cleanup systems. Quite often, the choice amongst alternatives is made on the basis of competitive bids for the installed capital equipment system, i.e., the low bidder on equipment. Quite obviously one cannot be casual about the fixed capital costs, and efforts should be made to minimize those capital costs consistent with a more comprehensive and more realistic view of the actual processing costs. The emphasis upon low bidding in the fixed capital category should not be allowed to obscure the dominant role of the annual noncapital expense in determining the true cost of cleanup operations.

### **b. Group-II, A-1**

This analytical group generally covers the majority of the original output specifications for this chapter of the final report. Both TCE and benzene are at a concentration of 10 ppm in the groundwater.

TABLE 27. LIFETIME COST ESTIMATES FOR TREATING GROUNDWATER  
USING A TRADITIONAL PACKED TOWER, BENZENE

Processing Costs per 1000 gallons Water*									
Variable (wgm)	Stripper Alone			Stripper Plus Carbon			Stripper Plus Catalysis		
	Fixed Capital	Expense	Total	Fixed Capital	Expense	Total	Fixed Capital	Expense	Total
100	0.1095	3.0787	3.1882	0.3840	9.2762	9.6602	0.1850	4.7162	4.9012
200	0.0692	1.7503	1.8195	0.2484	7.6029	7.8513	0.1084	3.3381	3.4465
300	0.0532	1.2879	1.3411	0.2007	6.8899	7.0906	0.0804	2.8589	2.9393
400	0.0443	1.0419	1.0862	0.1760	6.4240	6.6000	0.0654	2.6042	2.6696
500	0.0386	0.8890	0.9276	0.1607	6.0693	6.2300	0.0561	2.4461	2.5022
600	0.0345	0.7882	0.8227	0.1502	5.7801	5.9303	0.0496	2.3416	2.3912
700	0.0314	0.7102	0.7416	0.1426	5.5253	5.6679	0.0448	2.2611	2.3059
800	0.0289	0.6507	0.6796	0.1368	5.2993	5.4361	0.0410	2.1995	2.2405
900	0.0270	0.6061	0.6331	0.1322	5.0979	5.2301	0.0381	2.1534	2.1915
1000	0.0254	0.5672	0.5926	0.1285	4.9112	5.0397	0.0356	2.1132	2.1488
1100	0.0240	0.5373	0.5613	0.1254	4.7421	4.8675	0.0336	2.0822	2.1158
1200	0.0228	0.5122	0.5350	0.1227	4.5861	4.7088	0.0319	2.0562	2.0881
1300	0.0218	0.4879	0.5097	0.1205	4.4389	4.5594	0.0304	2.0311	2.0615
1400	0.0209	0.4693	0.4902	0.1185	4.3050	4.4235	0.0291	2.0118	2.0409
1500	0.0201	0.4506	0.4707	0.1168	4.1784	4.2952	0.0280	1.9926	2.0206

Note: Except for the water flow rate variable of the first column, all inputs are those shown in Table 26 for the base case.

\* Annually Inflated Current Dollars. Base Year = 1990.



TABLE 30. LIFETIME COST ESTIMATES FOR PROCESSING GROUNDWATER  
USING A ROTARY AIR STRIPPER, BENZENE

Processing Costs per 1000 gallons Water*									
Stripper Alone				Stripper Plus Carbon			Stripper Plus Catalysis		
Variable (wgm)	Fixed Capital	Expense	Total	Fixed Capital	Expense	Total	Fixed Capital	Expense	Total
100	0.1817	3.2765	3.4582	0.4560	9.4738	9.9298	0.2570	4.9138	5.1708
200	0.1133	1.9040	2.0173	0.2925	7.7567	8.0492	0.1525	3.4919	3.6444
300	0.0860	1.4323	1.5183	0.2335	7.0343	7.2678	0.1132	3.0033	3.1165
400	0.0708	1.1757	1.2465	0.2025	6.5579	6.7604	0.0919	2.7381	2.8300
500	0.0609	1.0157	1.0766	0.1830	6.1960	6.3790	0.0784	2.5728	2.6512
600	0.0539	0.9138	0.9677	0.1696	5.9057	6.0753	0.0690	2.4672	2.5362
700	0.0486	0.8307	0.8793	0.1598	5.6457	5.8055	0.0619	2.3815	2.4434
800	0.0444	0.7673	0.8117	0.1522	5.4159	5.5681	0.0565	2.3162	2.3727
900	0.0410	0.7223	0.7633	0.1462	5.2141	5.3603	0.0521	2.2696	2.3217
1000	0.0382	0.6804	0.7186	0.1413	5.0244	5.1657	0.0485	2.2264	2.2749
1100	0.0359	0.6502	0.6861	0.1372	4.8550	4.9922	0.0455	2.1951	2.2406
1200	0.0338	0.6253	0.6591	0.1338	4.6992	4.8330	0.0429	2.1693	2.2122
1300	0.0321	0.5983	0.6304	0.1308	4.5493	4.6801	0.0407	2.1415	2.1822
1400	0.0305	0.5798	0.6103	0.1282	4.4155	4.5437	0.0387	2.1223	2.1610
1500	0.0291	0.5589	0.5880	0.1259	4.2867	4.4126	0.0370	2.1009	2.1379

Note: Except for the water flow rate variable of the first column, all inputs are those shown in Table 26 for the base case.

\* Annually inflated current dollars. Base Year = 1990.

There are 12 data configurations in this group (see Appendix C, Table C.1, and Tables C.2 through C.13). Single variable sensitivity analyses from this group are presented graphically in the following Figures 67-80. Figures 69 and 72 illustrate comparative information.

The base case condition is marked on each of these graphs. For the base case in all 12 data sets, the following costs in dollars per 1000 gallons of groundwater processed are found. These are operating lifetime processing costs, adjusted for inflation.

CONFIGURATION	TCE	BENZENE
Packed stripper	\$0.91	\$0.92
Stripper plus carbon	\$2.10	\$6.23
Stripper plus catalysis	\$2.04	\$2.50
Centrifugal stripper	\$1.06	\$1.07
Stripper plus carbon	\$2.24	\$6.37
Stripper plus catalysis	\$2.19	\$2.65

Evaluation of the following graphical information indicates:

- There are significant economies of scale, and a cost preference for single, larger rather than multiple, smaller units.
- At equal TCE and benzene concentrations, carbon adsorption treatment of the off gas is relatively more expensive for the benzene. This is because the benzene is simply a component of a hypothetical jet fuel, and the carbon system must be large enough to accommodate the other jet fuel components as well.
- No cost differences between a packed column and a centrifugal stripper system can be shown, especially given the probable uncertainty range in the cost estimates. That uncertainty is greater in the case of a centrifugal stripper. A more detailed approach to centrifugal stripper cost analyses in the future might make differences, if any, clearer.
- Cost considerations favor lower values of the stripping factor.
- Flooding factor variations have an insignificant impact upon processing costs.

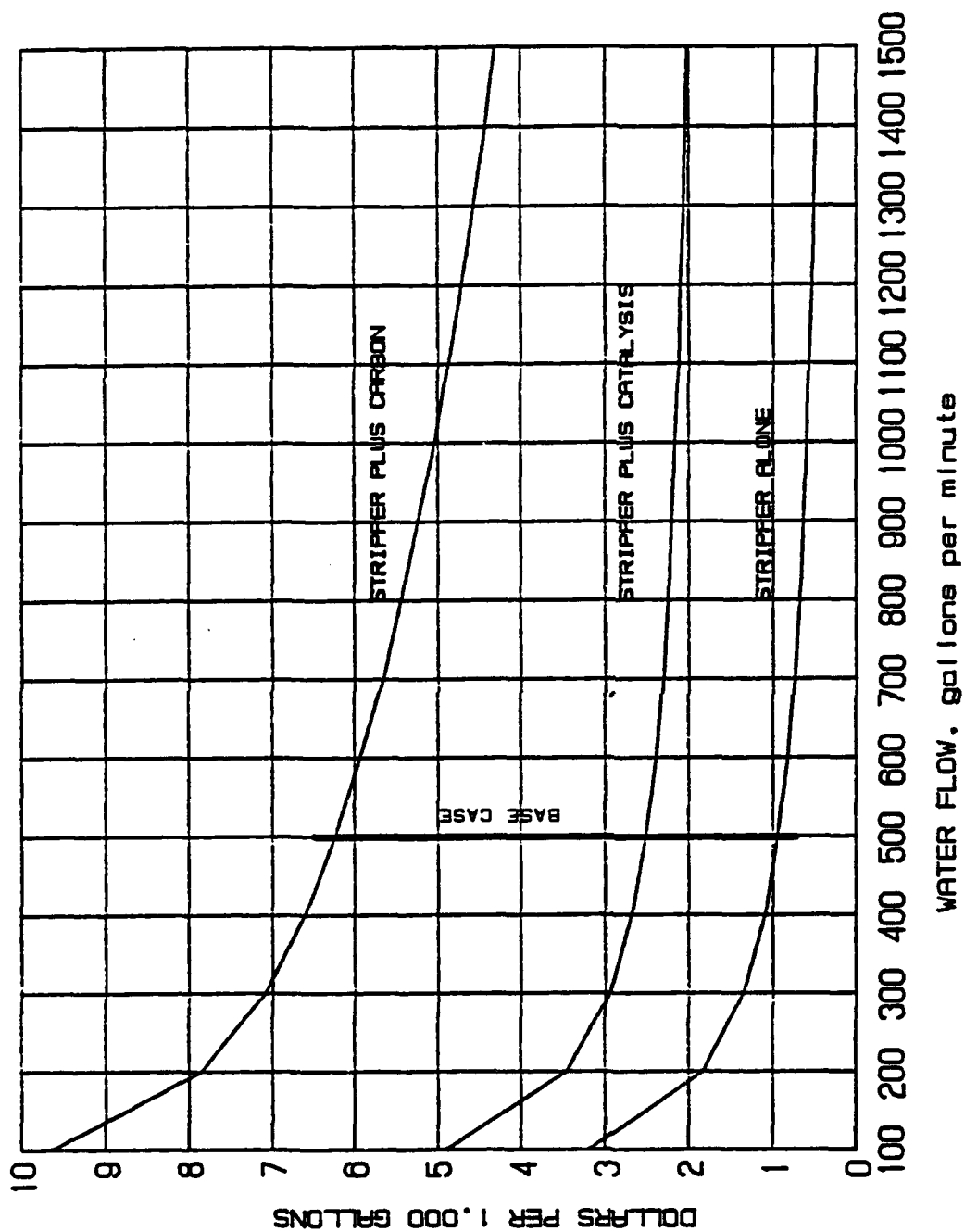


Figure 67. Operating Lifetime Processing Costs as a Function of Capacity for an Air Stripping System Utilizing a Traditional Packed Tower for Removing Benzene from Groundwater (Method A-1).

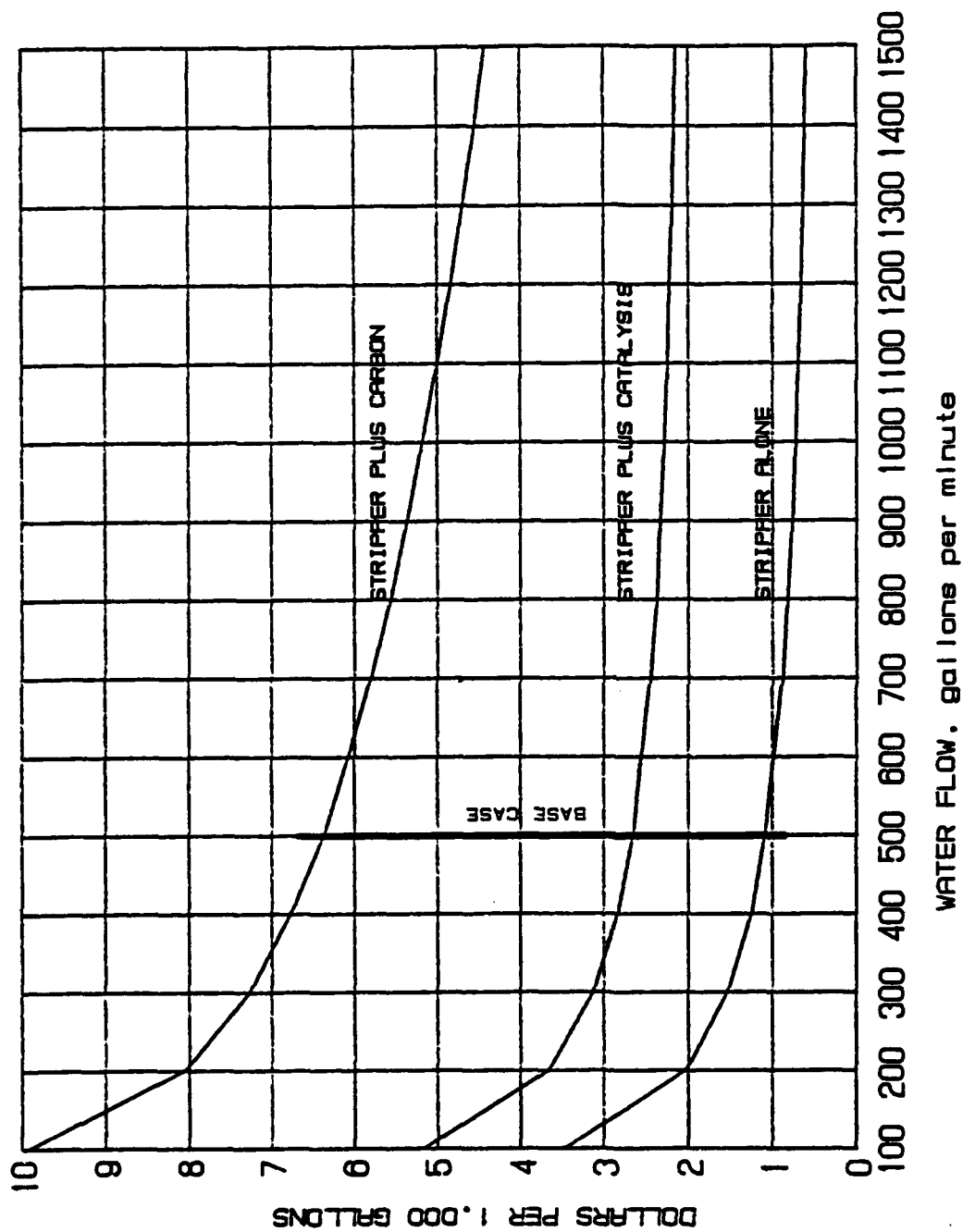


Figure 68. Operating Lifetime Processing Costs as a Function of Capacity for an Air Stripping System Utilizing a Rotary Air Stripper for Removing Benzene from Groundwater (Method A-1).

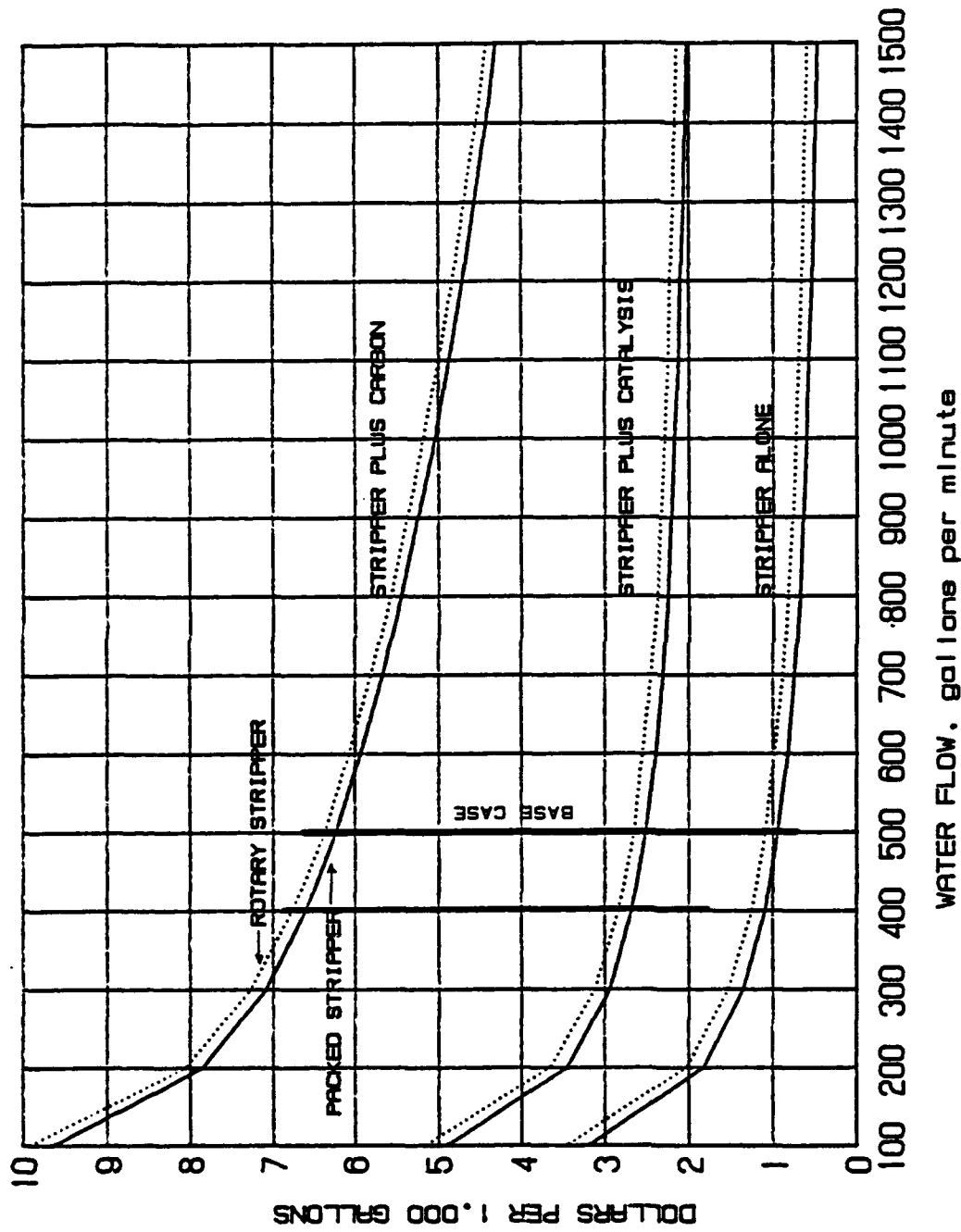


Figure 69. Comparison of Lifetime Processing Costs as a Function of Capacity for an Air Stripping System for Benzene Removal from Groundwater Featuring a Traditional Packed Tower vs. a Similar Purpose System Featuring a Rotary Air Stripper (Method A-1).

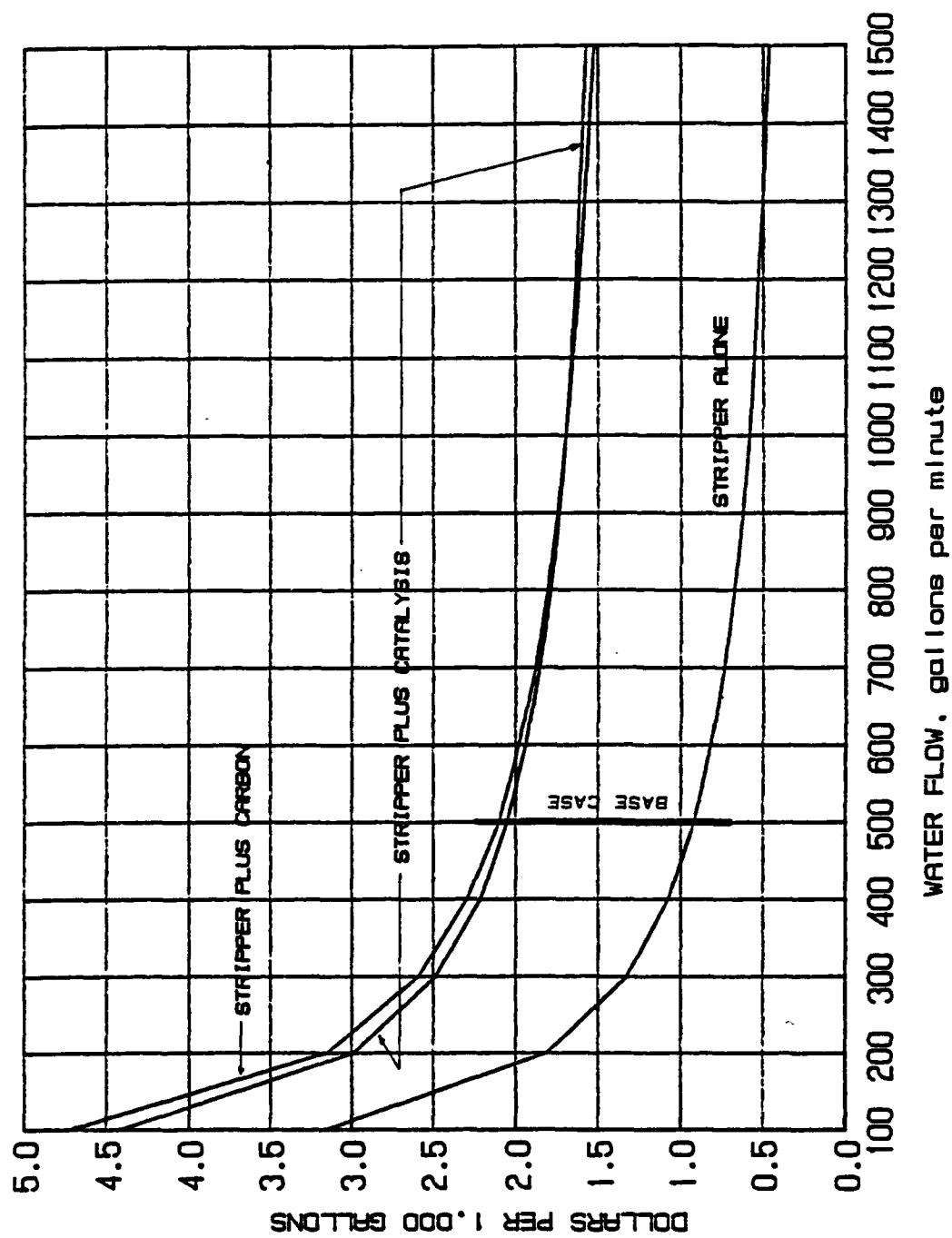


Figure 70. Operating Lifetime Processing Costs as a Function of Capacity for an Air Stripping System Utilizing a Traditional Packed Tower for Removing TCE from Groundwater (Method A-1).

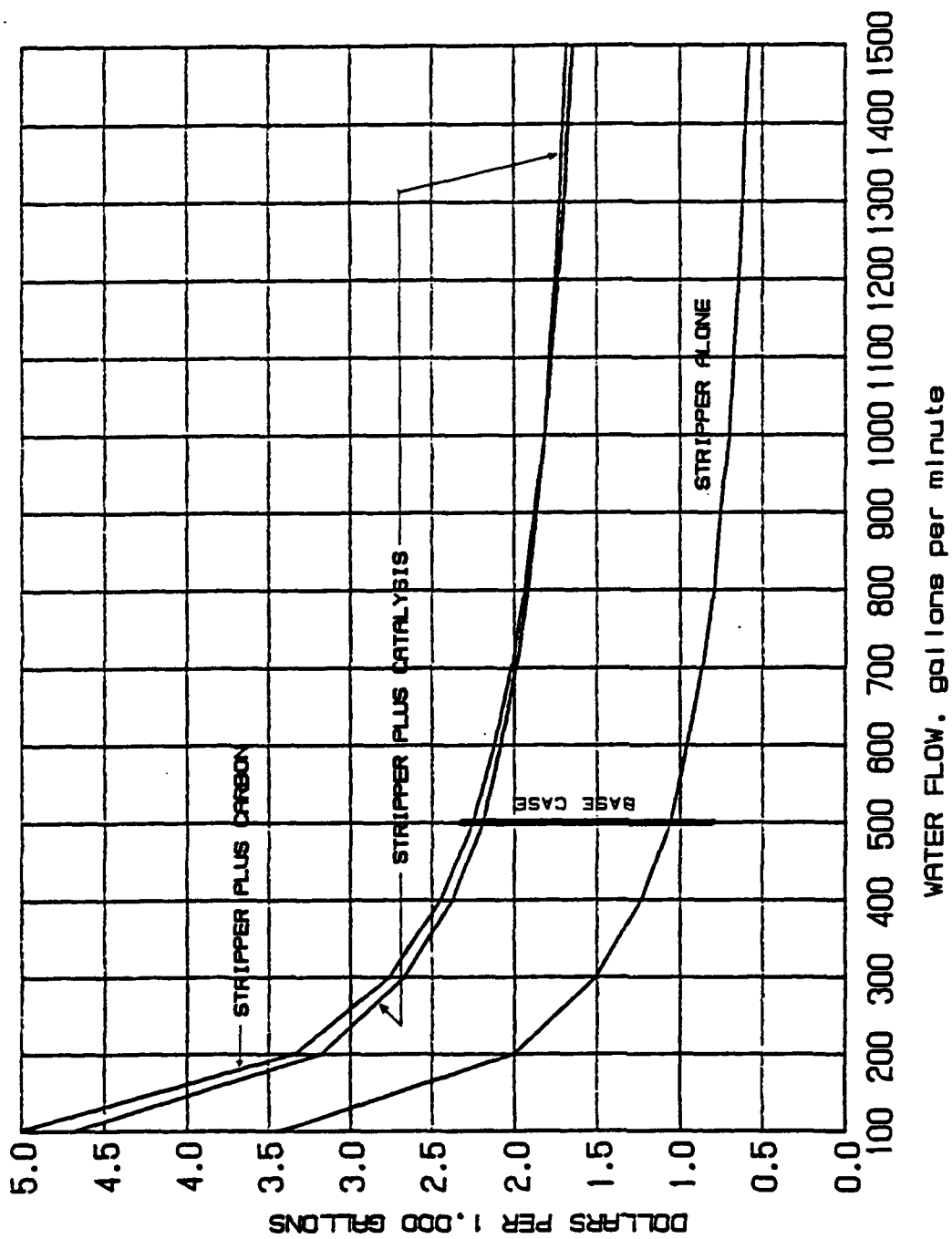


Figure 71. Operating Lifetime Processing Costs as a Function of Capacity for an Air Stripping System Utilizing a Rotary Air Stripper for Removing TCE from Groundwater (Method A-1).

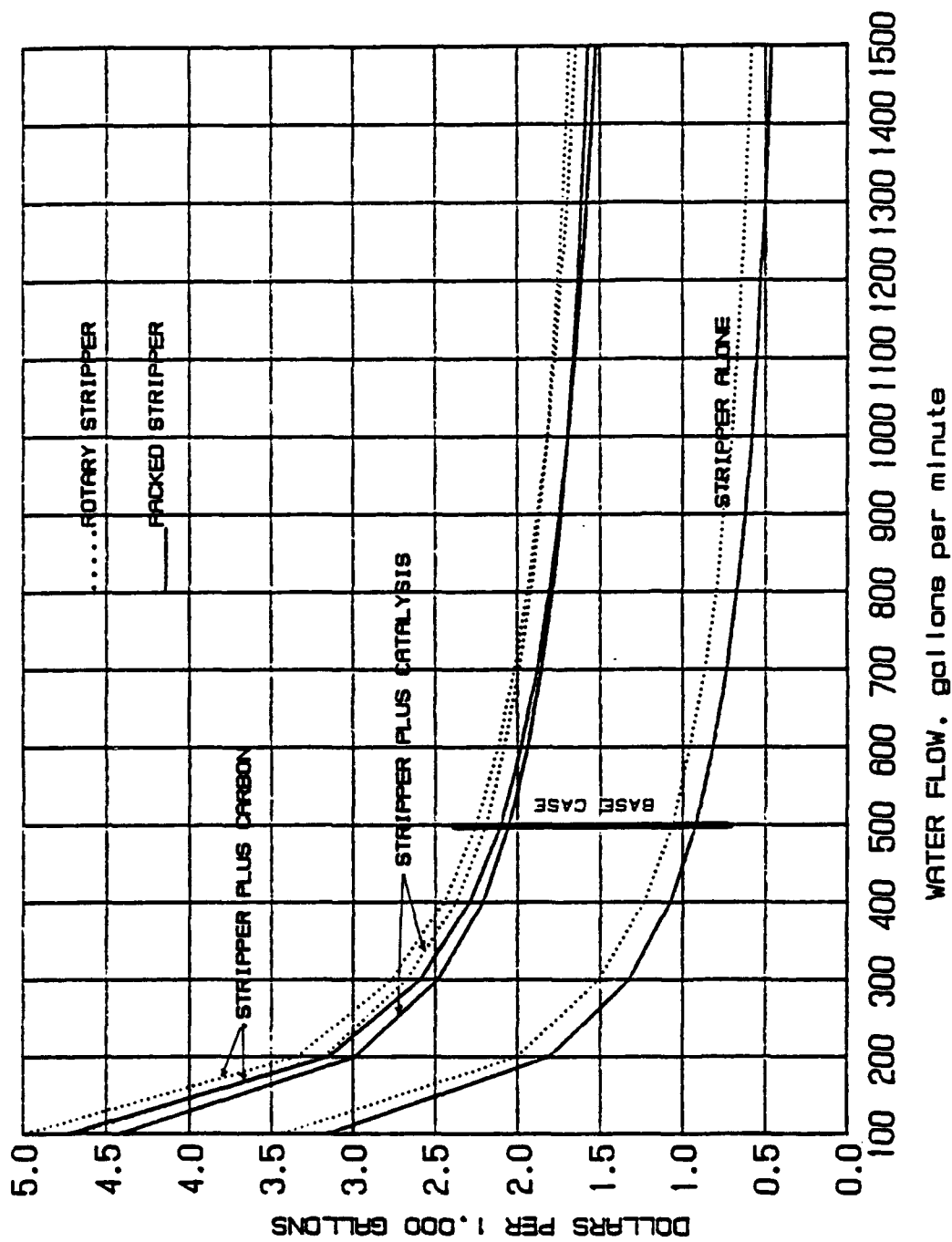


Figure 72. Comparison of Lifetime Processing Costs as a Function of Capacity for an Air Stripping System for TCE Removal from Groundwater Featuring a Traditional Packed Tower vs. a Similar Purpose System Featuring a Rotary Air Stripper (Method A-1).



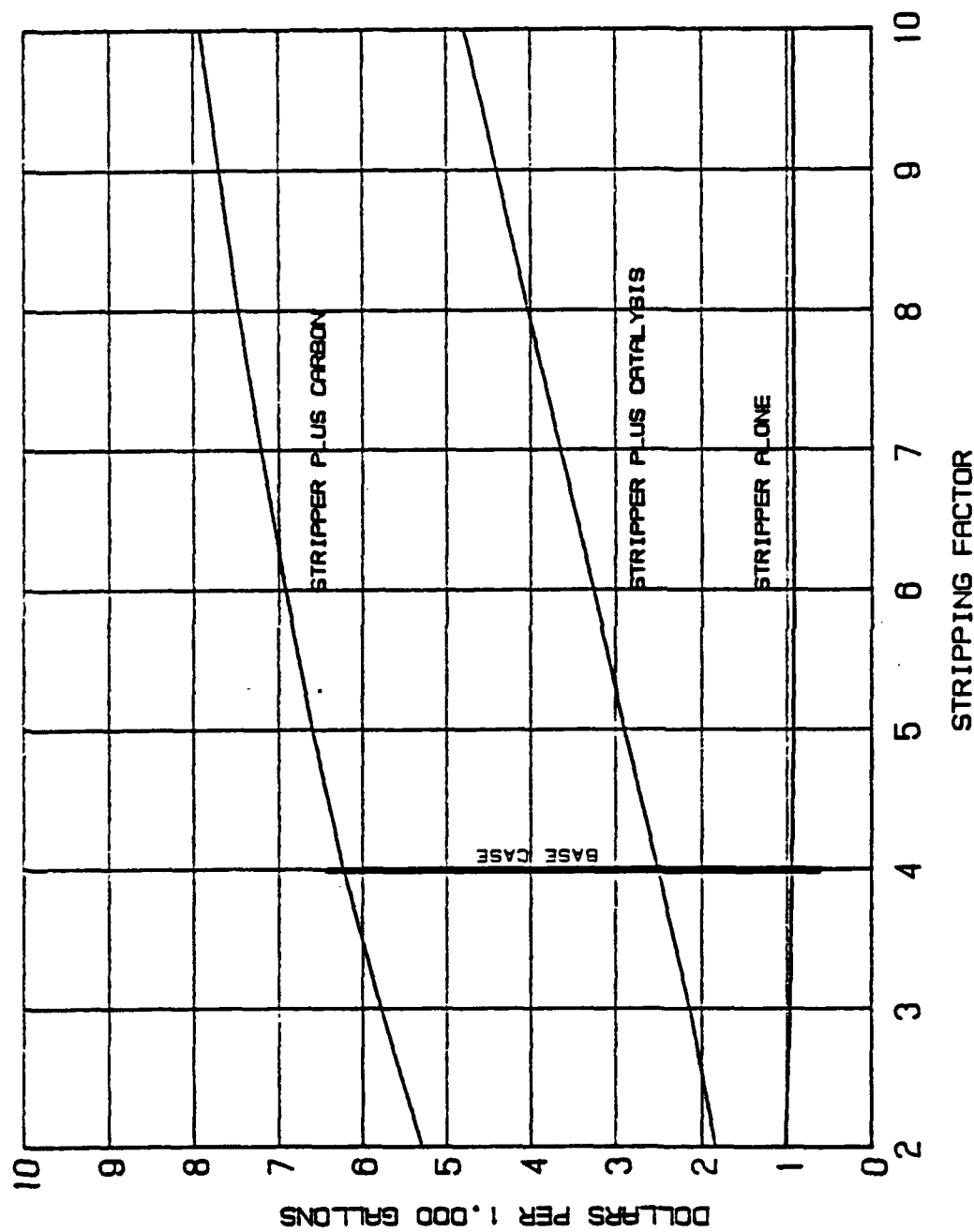


Figure 73. Operating Lifetime Processing Costs as a Function of Stripping Factor for an Air Stripping System Utilizing a Traditional Packed Tower for Removing Benzene from Groundwater (Method A-1).

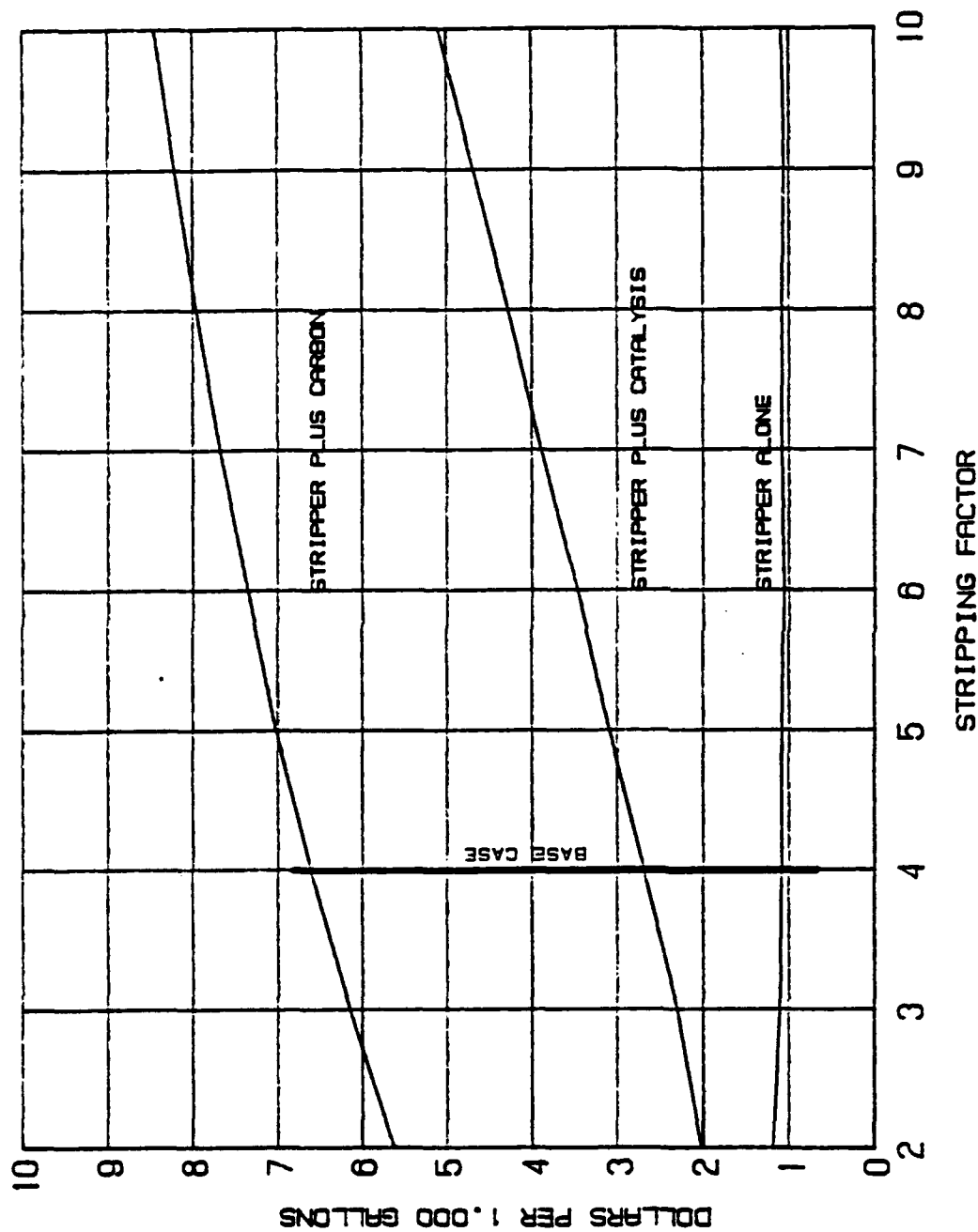


Figure 74. Operating Lifetime Processing Costs as a Function of Stripping Factor for an Air Stripping System Utilizing a Rotary Air Stripper for Removal of Benzene from Groundwater (Method A-1).

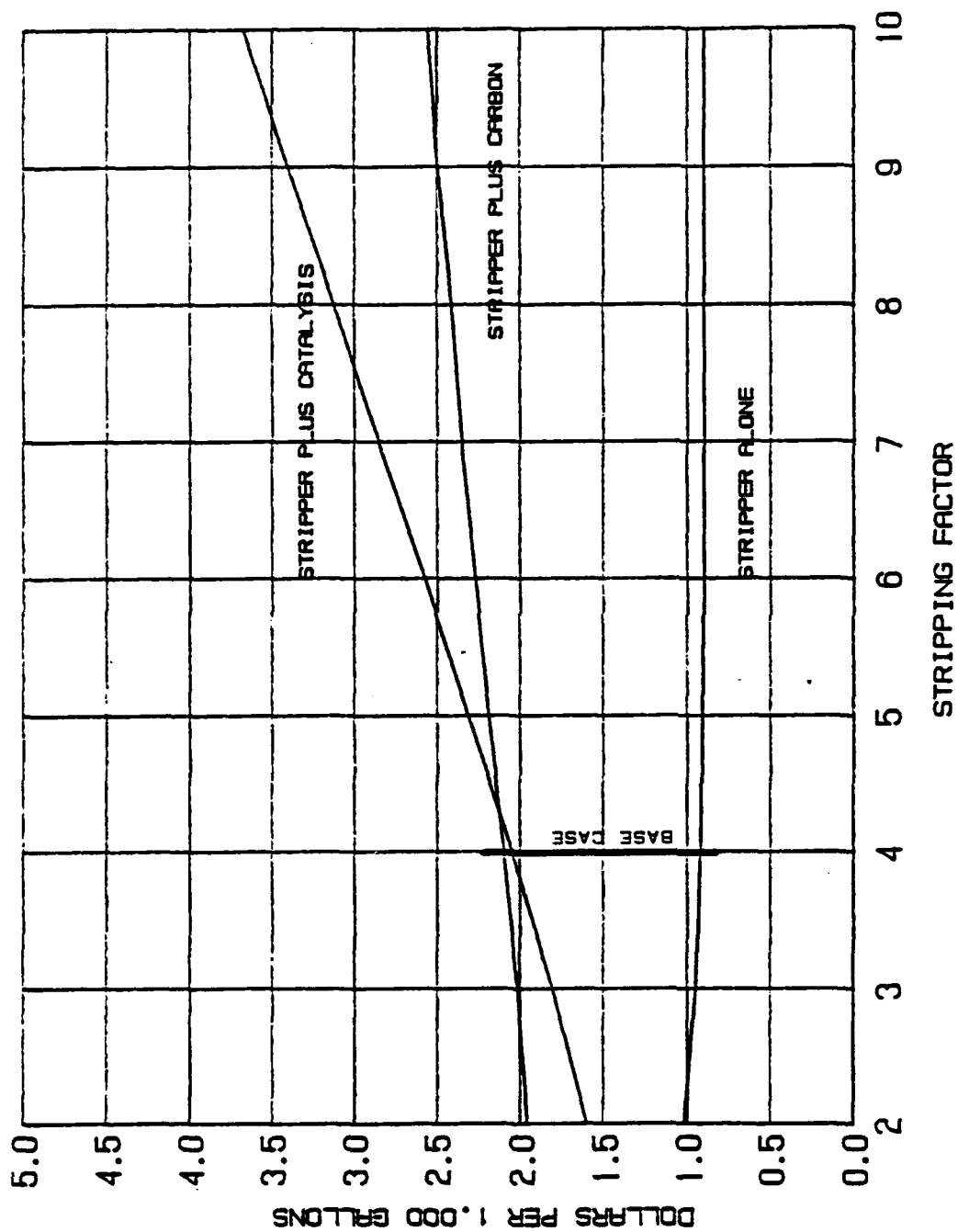


Figure 75. Operating Lifetime Processing Costs as a Function of Stripping Factor for an Air Stripping System Featuring a Traditional Packed Tower for Removing TCE from Groundwater (Method A-1).

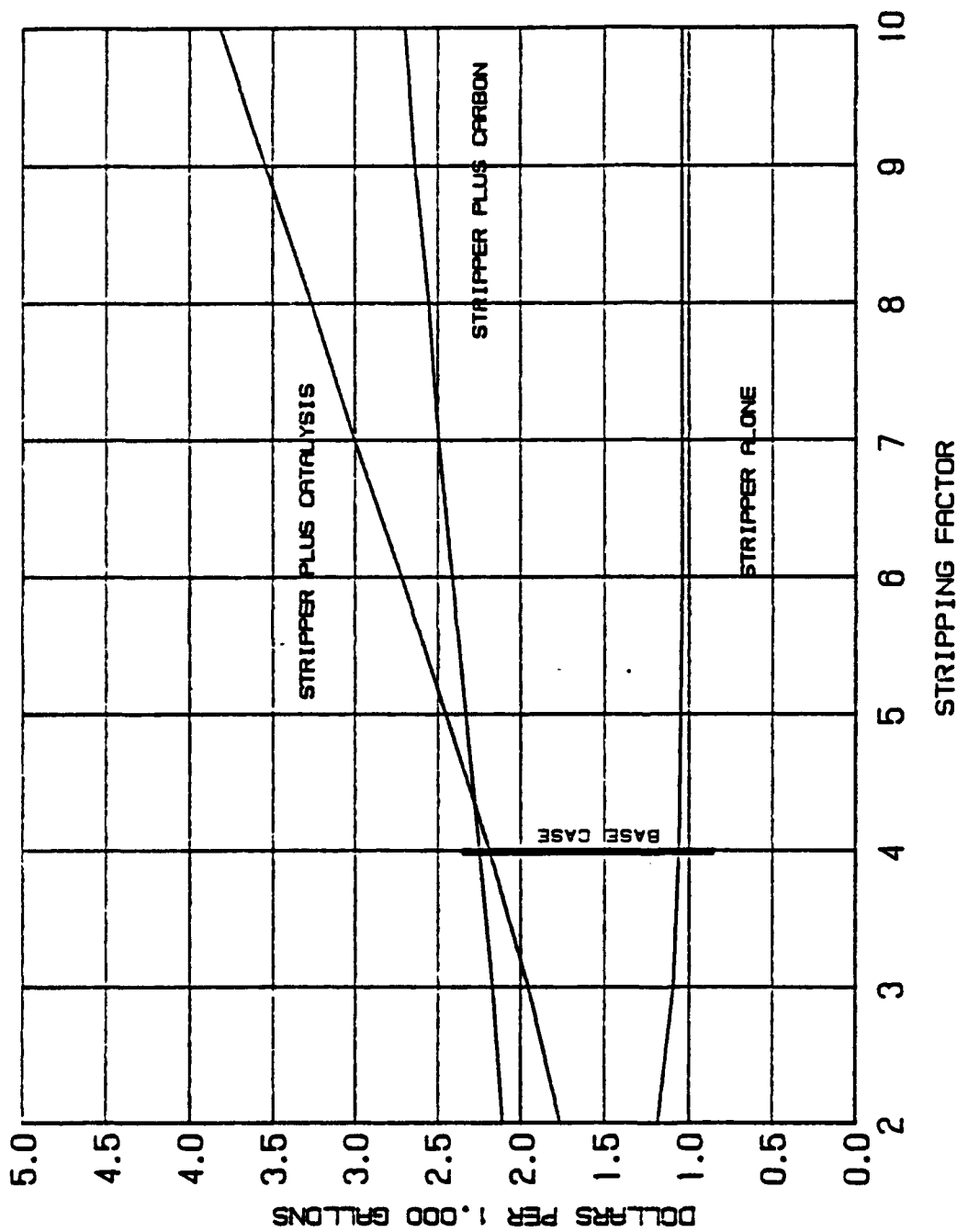


Figure 76. Operating Lifetime Processing Costs as a Function of Stripping Factor for an Air Stripping System Utilizing a Rotary Air Stripper for Removal of TCE from Groundwater (Method A-1).

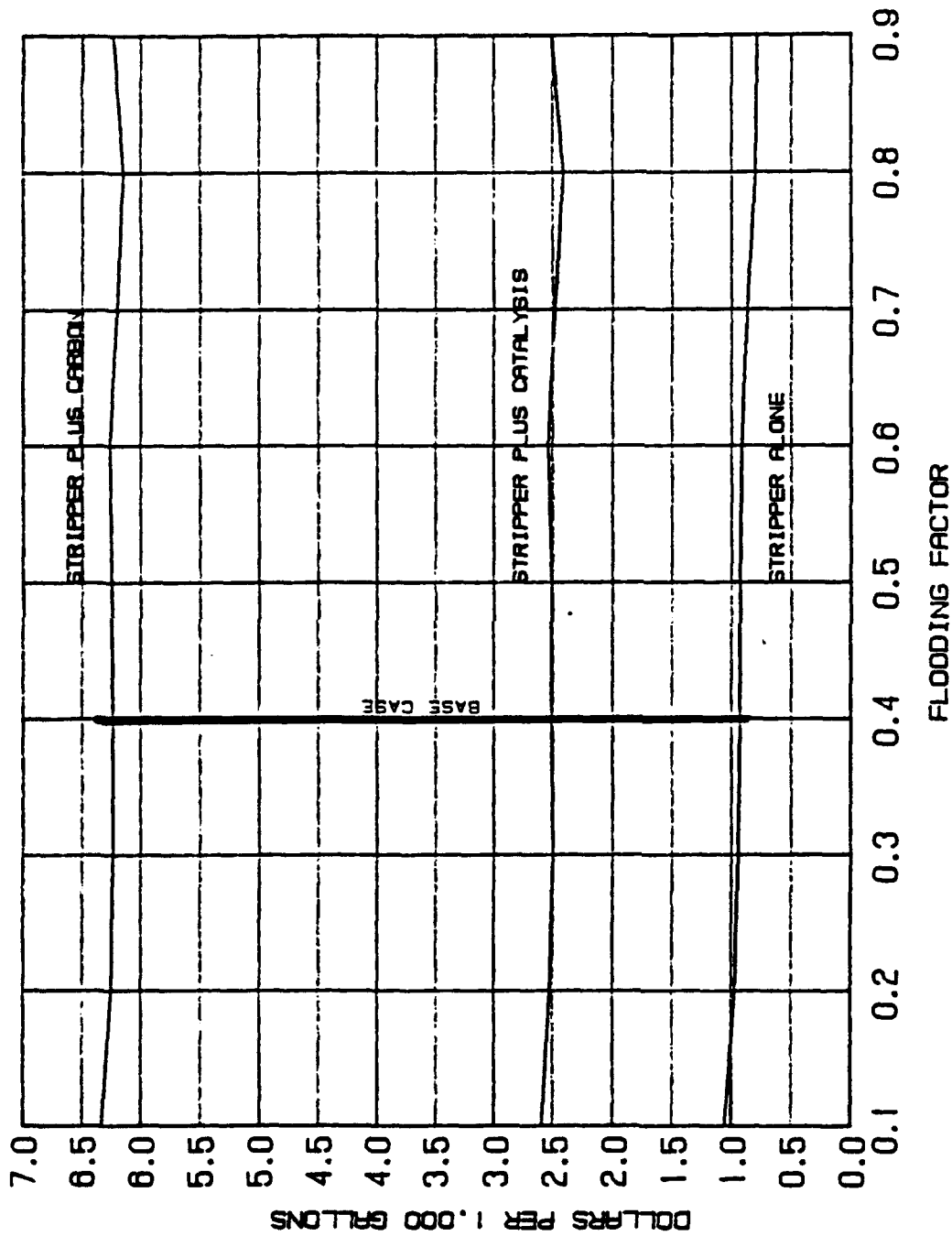


Figure 77. Operating Lifetime Processing Costs as a Function of the Flooding Factor (Fraction of Flooding) for an Air Stripping System Featuring a Traditional Packed Tower for Removing Benzene from Groundwater (Method A-1).

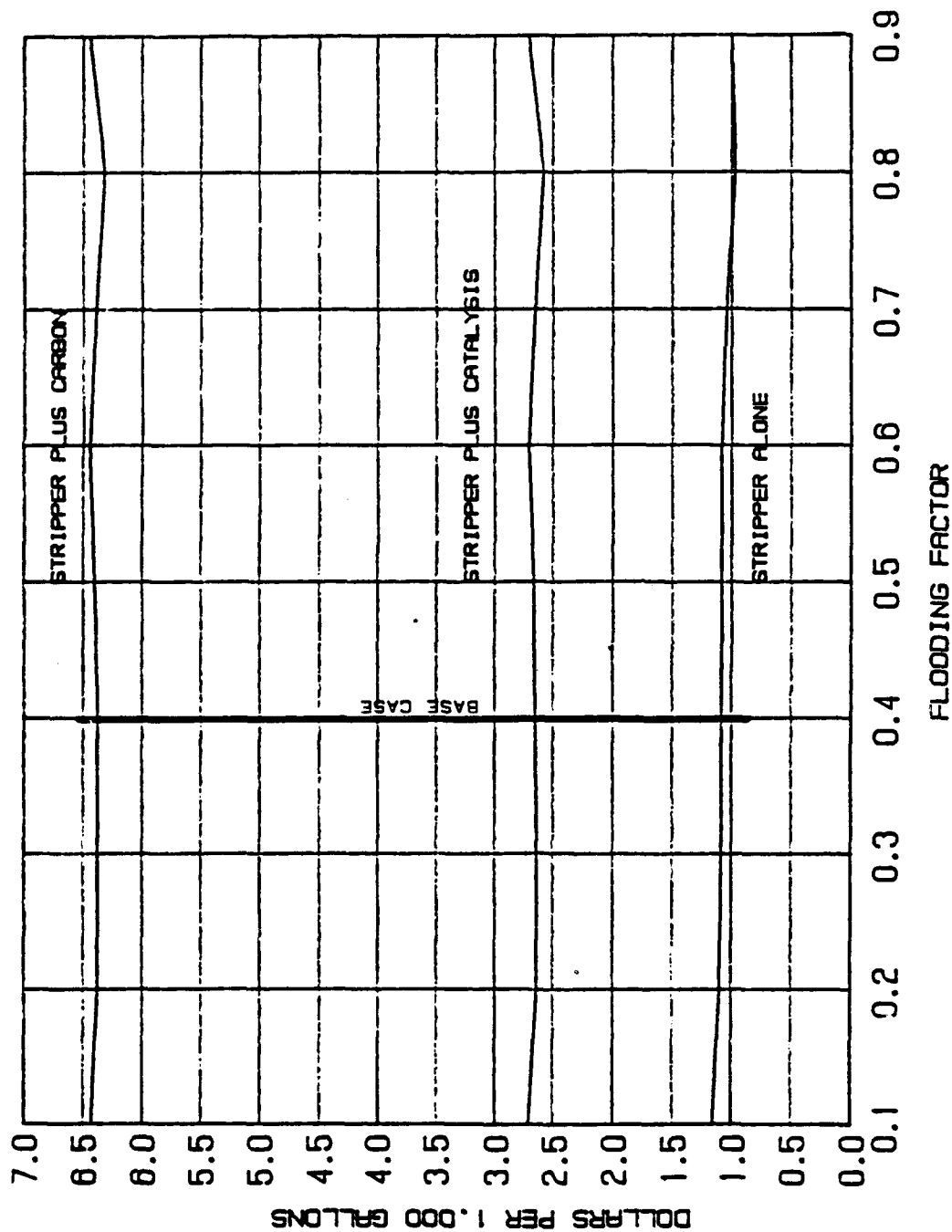


Figure 78. Operating Lifetime Processing Costs as a Function of the Flooding Factor (Fraction of Flooding) for an Air Stripping System Featuring a Rotary Air Stripper for Removing Benzene from Groundwater (Method A-1).

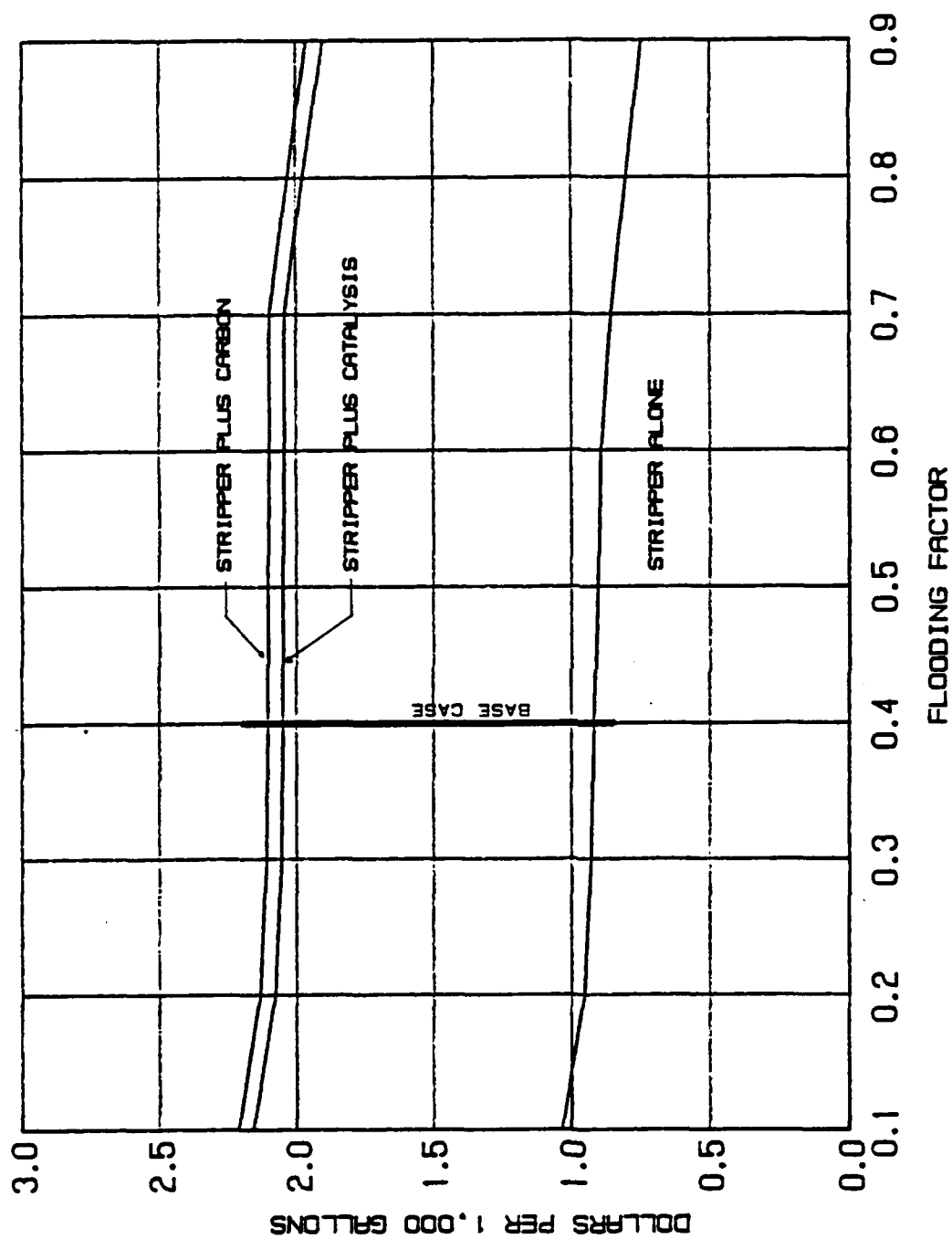


Figure 79. Operating Lifetime Processing Costs as a Function of the Flooding Factor (Fraction of Flooding) for an Air Stripping System Featuring a traditional Packed Tower for Removing TCE from Groundwater (Method A-1).

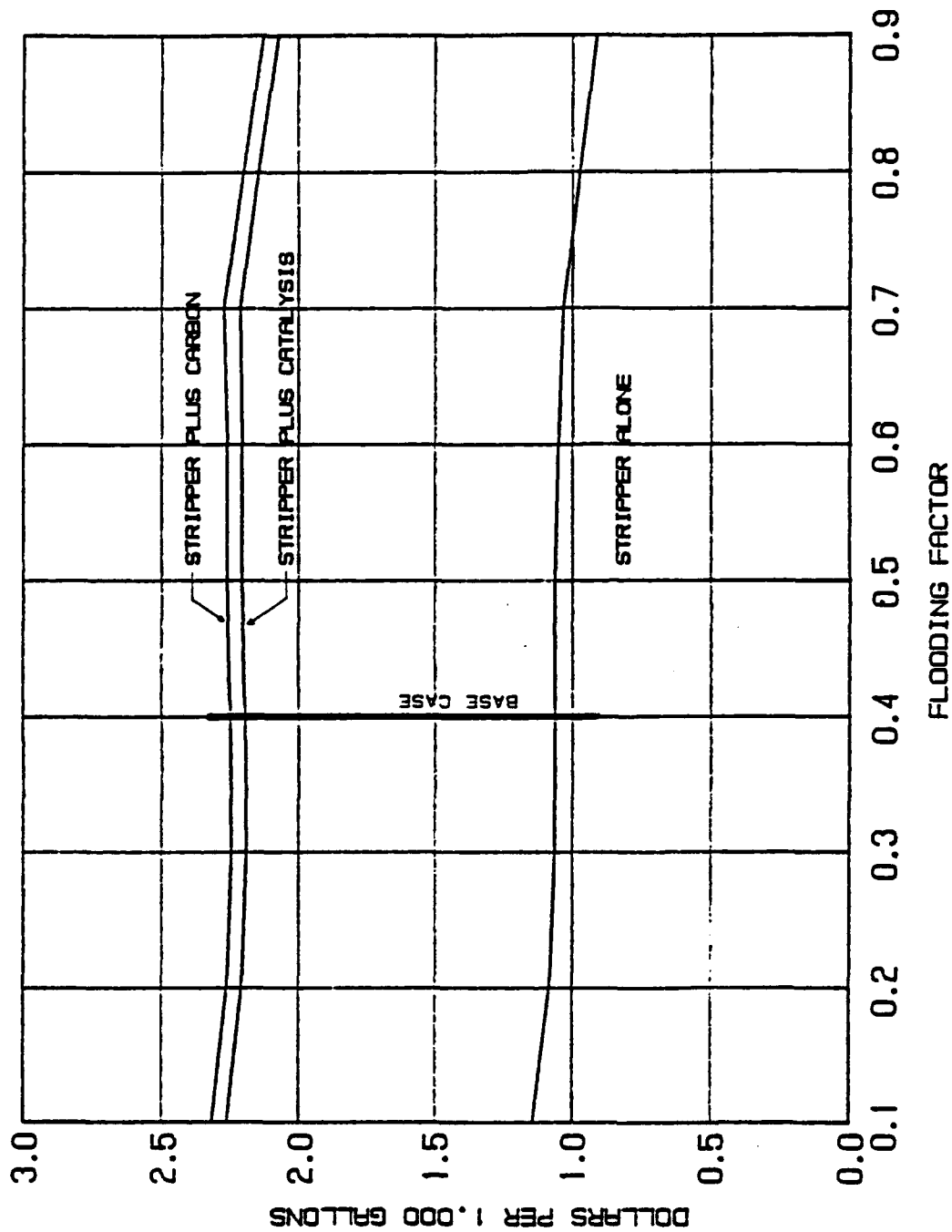


Figure 80. Operating Lifetime Processing Costs as a Function of the Flooding Factor (Fraction of Flooding) for an Air Stripping System Featuring a Rotary Air Stripper for Removing TCE from Groundwater (Method A-1).



The cases shown in Figures 67-80 are cuts through a four-dimensional cost "surface," and provide single variable cost sensitivity analyses. They do not, however, illustrate the complete "cost surface," a task beyond the scope of the current study. Thus alone they do not necessarily show the minimum cost combination for the three input variables analyzed.

As further background, the fixed capital and the annual expense cost estimates in 1990 dollars for the base case in this group are:

Configuration	TCE		BENZENE	
	Fixed Capital	Annual Expense	Fixed Capital	Annual Expense
Packed stripper	\$169,691	\$113,707	\$172,226	\$115,149
Carbon adsorption	\$236,060	\$146,014	\$545,623	\$689,619
Catalytic incineration	\$ 74,403	\$149,848	\$ 78,257	\$210,772
Rotary stripper	\$272,112	\$126,529	\$272,112	\$128,496
Carbon adsorption	\$236,060	\$146,014	\$545,623	\$689,619
Catalytic incineration	\$ 74,403	\$149,848	\$ 78,257	\$210,772

These base case cost figures are for the individual units, and are not cumulative.

#### c. Group III, A-1

This data group, presented in Figures 81 through 85, deals with a collection of a single variable analyses, all for TCE as the groundwater contaminant, and all for a traditional packed column stripper plus the two options for off-gas treatment. The analytical results shown here are similar for the case of benzene at the same concentration level in the groundwater. The purpose of this set is to provide a broadened view of how the various input parameters may affect the processing costs per 1000 gallons of water, and also to demonstrate the versatility of the supporting software developed for this project. The base case is marked on each of the graphs, and for the base case (TCE) we have the following lifetime processing costs:

Packed stripper	\$0.91
Stripper plus carbon	\$2.10
Stripper plus catalysis	\$2.04

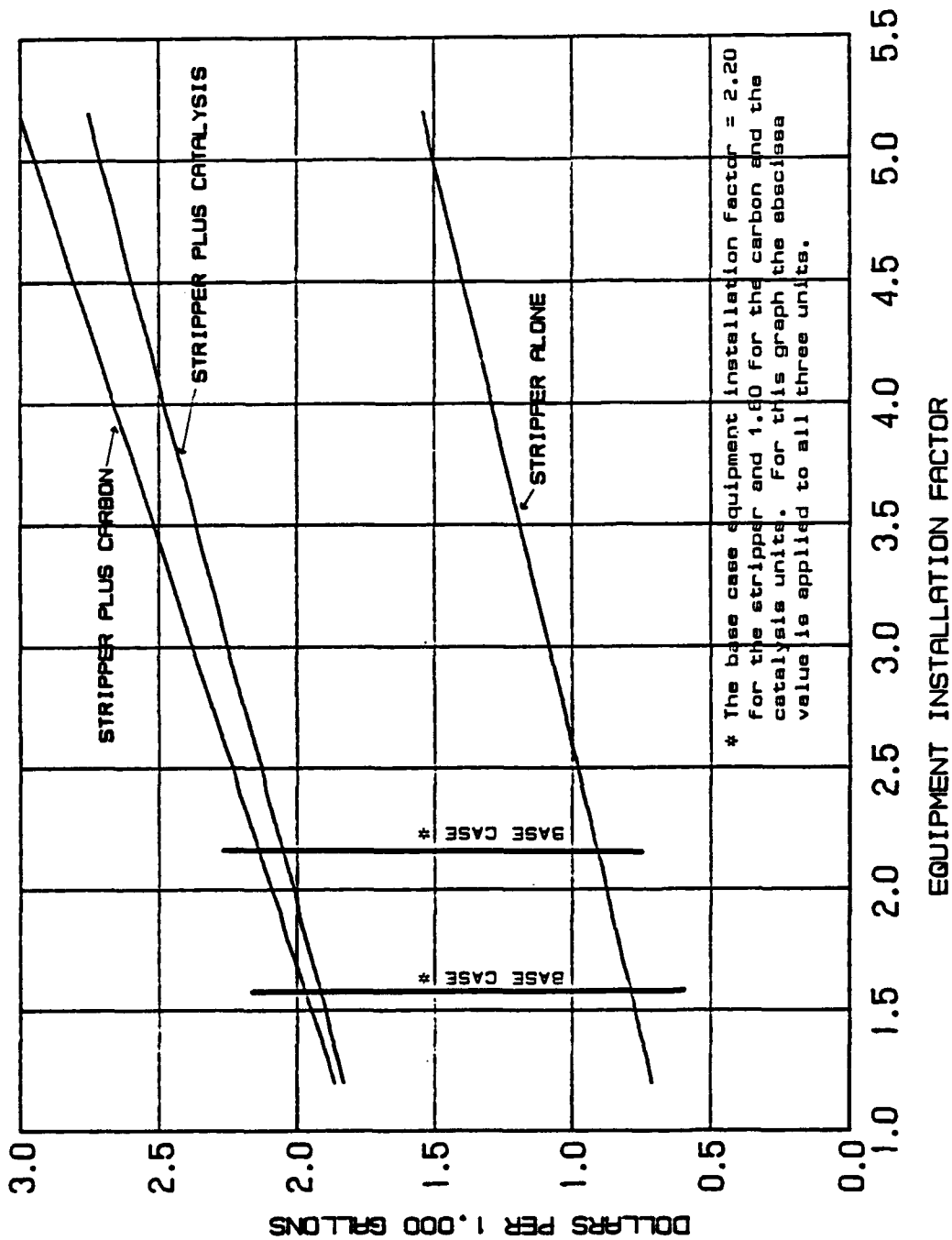


Figure 81. Operating Lifetime Processing Costs as a Function of Equipment Installation Factor for an Air Stripper System Featuring a Traditional Air Stripper for TCE Removal from Groundwater (Method A-1).

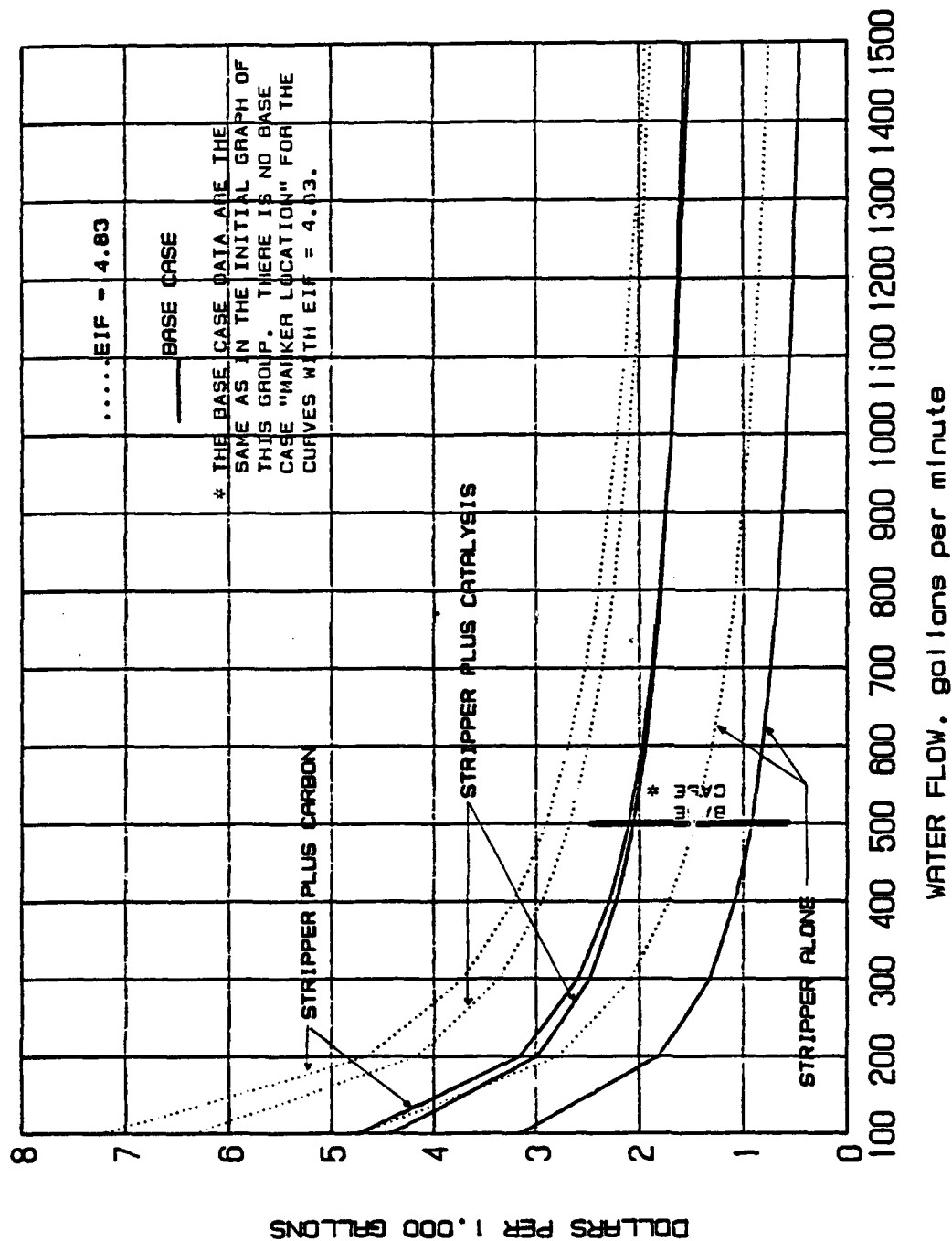


Figure 82. Operating Lifetime Processing Costs as a Function of Capacity for an Air Stripping System Featuring a Traditional Packed Tower for TCE Removal from Groundwater (Method A-1). [Except for Variation of Equipment Installation Factor (EIF) Method A and Method B factors are used]

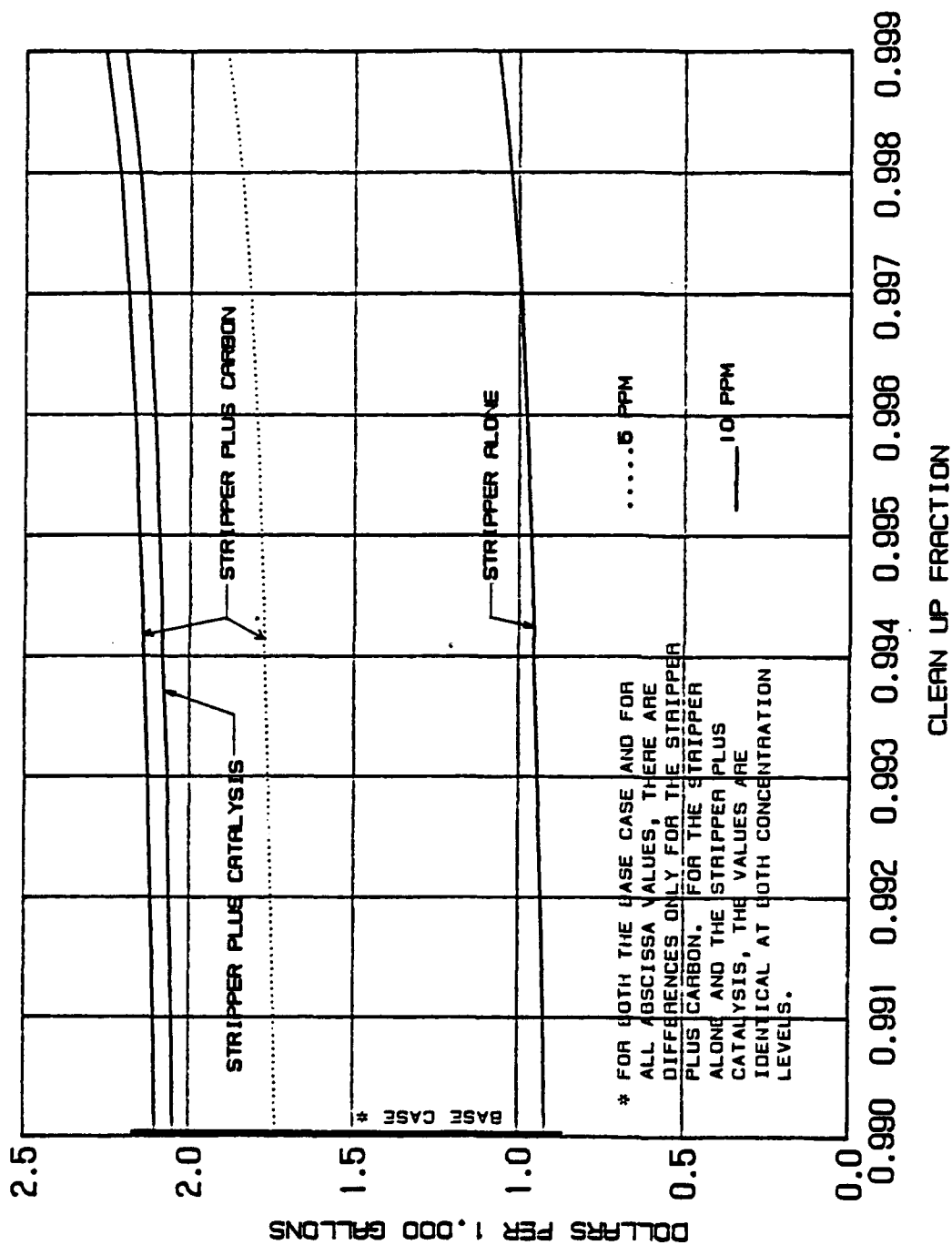


Figure 83. Operating Lifetime Processing Costs as a Function of the Cleanup Fraction of TCE from Groundwater in an Air Stripper System Featuring a Traditional Packed Tower (Method A-1).

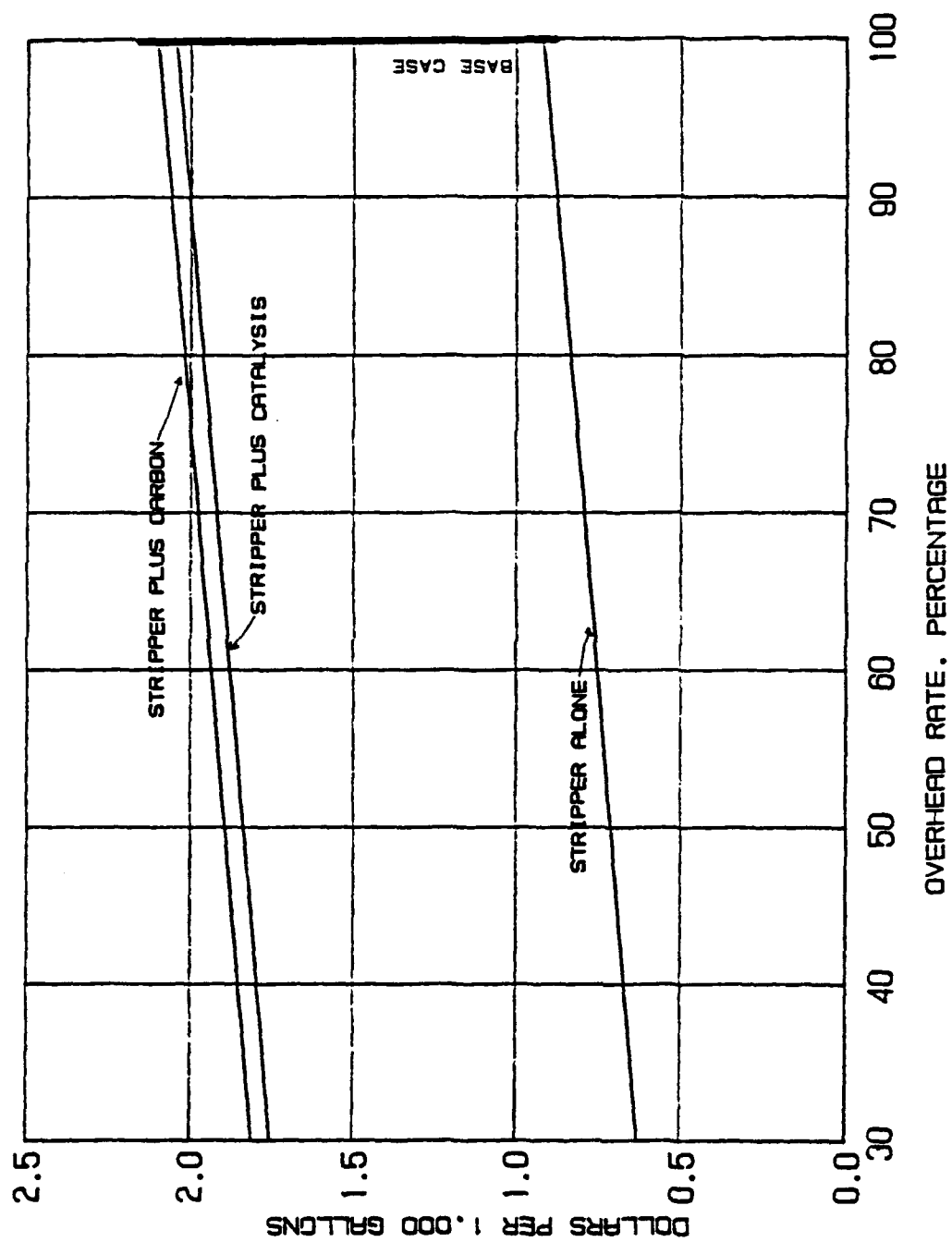


Figure 84. Operating Lifetime Processing Costs as a Function of Overhead Rate for an Air Stripper System Featuring a Traditional Packed Tower for TCE Removal from Groundwater (Method A-1).

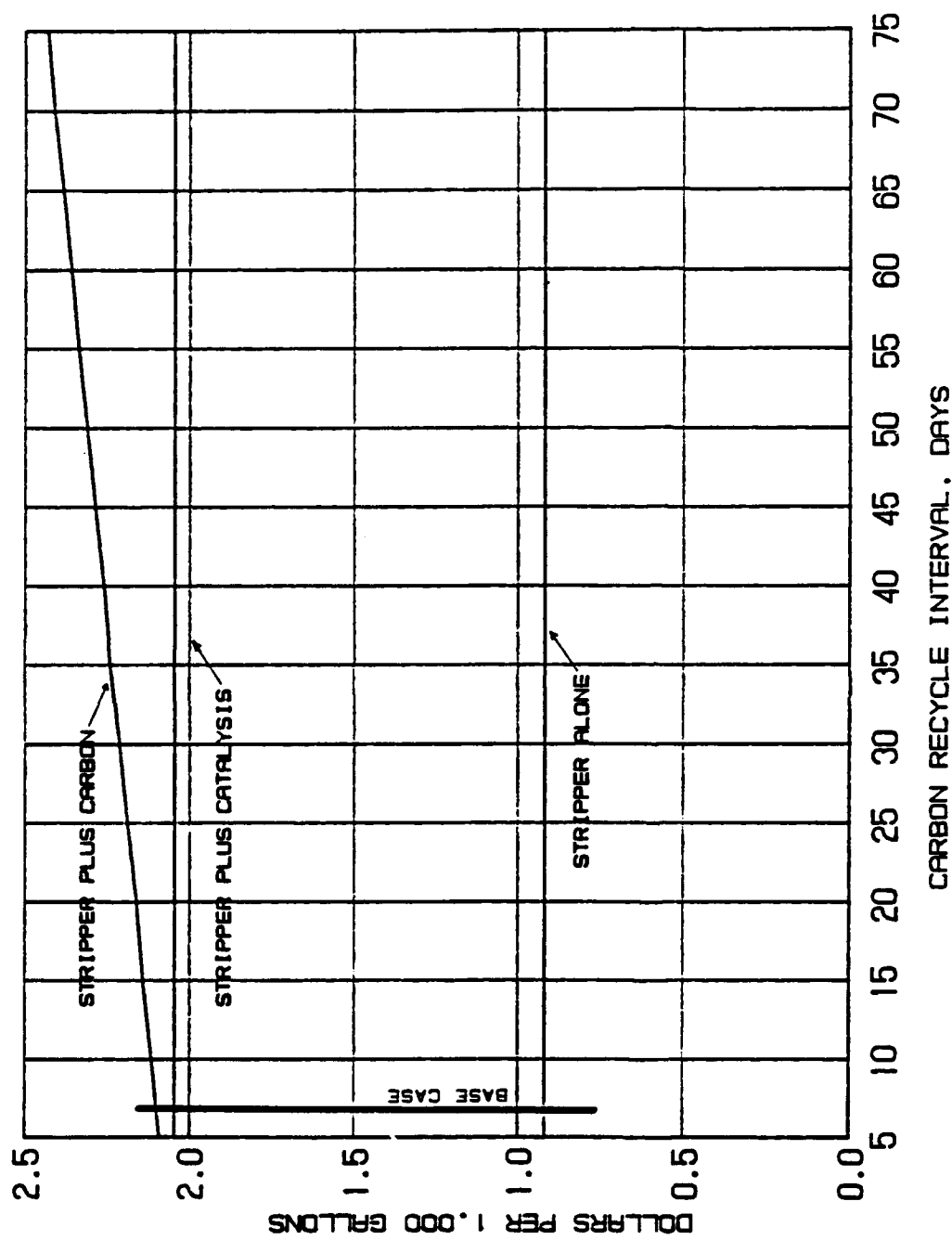


Figure 85. Operating Lifetime Processing Costs as a Function of Carbon Recycle Interval for an Air Stripping System Featuring a Traditional Packed Tower for TCE Removal from Groundwater (Method A-1).

The single variable sensitivity analyses contained here are as follows:

VARIABLE	FIGURE
Water flow rate	70
Stripping factor	75
Flooding factor	79
Installation factor	81
Water flow rate at	82
Cleanup factor	83
Overhead rate	84
Carbon recycle interval	85

The tabular source data for these graphs are found in Appendix C. The analytical organization for the graphs is the same as for the preceding group and the trend relationships need no comment.

As further background, the fixed capital and the annual expense cost estimates for the base case in this group are:

CONFIGURATION	FIXED CAPITAL	ANNUAL EXPENSE
Packed stripper	\$169,791	\$113,707
Carbon adsorption	\$236,060	\$146,014
Catalytic incineration	\$ 74,403	\$149,848

**d. Group IV, A-1**

This is a special group, requested by USAF\*. The special conditions are:

Centrifugal stripper (packed stripper included also)

5/8 inch Flexirings®

Contaminant is TCE

TCE concentration in groundwater = 5 ppm

Water flow rate = 200 gallons/minute

Temperature = 10°C

Cleanup factor = 99 and 99.9 percent

Stripping factor = 8

Flooding factor = 0.4

The two cleanup factor values of 99 and 99.9 percent are handled by running data with CUF as the single variable. The results are shown in Figure 86.

Processing costs per 1000 gallons of water for these conditions are:

CONFIGURATION	CLEANUP FACTOR	
	99%	99.9%
Packed stripper	\$1.81	\$2.05
Stripper plus carbon	\$3.16	\$3.43
Stripper plus catalysis	\$4.92	\$5.17
Centrifugal stripper	\$1.99	\$2.22
Stripper plus carbon	\$3.34	\$3.59
Stripper plus catalysis	\$5.10	\$5.34

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\*Elliott, M. G., Personal Communication, Oak Ridge National Laboratory, 06 June 1989.



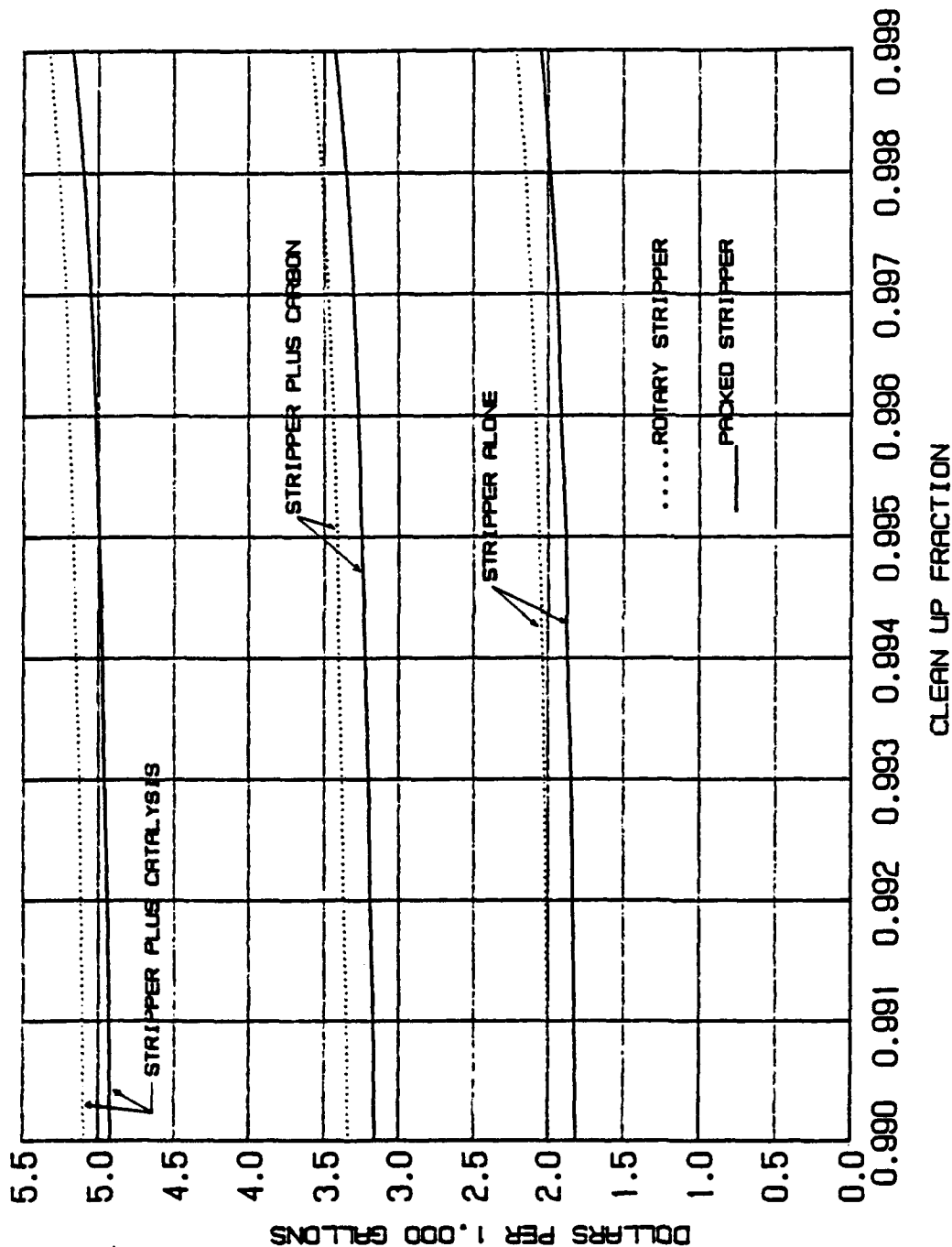


Figure 86. Operating Lifetime Processing Costs, for a USAF Special Case, as a Function of Cleanup Fraction for an Air Stripping System Featuring a Rotary Air Stripper and a Traditional Packed Tower for TCE Removal from Groundwater (Method A-1).

Cost estimates for the two levels of clean up, as found in the separately bound computer printout pages, are:

	FOR 99%		FOR 99.9%	
	FIXED CAPITAL	ANNUAL EXPENSE	FIXED CAPITAL	ANNUAL EXPENSE
Packed stripper	\$120,514	\$ 90,972	\$150,021	\$102,231
Carbon adsorption	\$194,545	\$ 60,288	\$194,687	\$ 61,400
Catalytic incineration	\$ 75,193	\$165,270	\$ 75,193	\$166,079
Centrifugal stripper	\$202,474	\$ 95,076	\$202,474	\$107,346
Carbon adsorption	\$194,545	\$ 60,288	\$194,687	\$ 61,400
Catalytic incineration	\$ 75,193	\$165,270	\$ 75,193	\$166,079

It is evident from these data that there is little difference in the total processing costs at 99 and 99.9 percent cleanup, for the stated operating conditions.

**c. Group V, A-2**

A decision was made to add an evaluation of the processing costs per 1000 gallons of groundwater at a benzene contaminant level in the groundwater which would simulate field test conditions at Eglin AFB. The benzene concentration selected was 0.100 ppm.

In order to run at this lower concentration level, it was also necessary to revise the constants of the Freundlich Equation in the computer program. The revised values were estimated using the SPEQ.FOR computer program.

The following six graphs, Figures 87-92, provide the information on the lifetime processing costs per 1000 gallons of groundwater, and for three different input variables. Except for the reduction in the contaminant concentration, all other input values remain as for the base case, shown in Table 26.

Information for both packed column and centrifugal strippers is provided in the graphs for this group. On each graph, data from an earlier group with the contamination level at 10 ppm are included for comparison purposes.

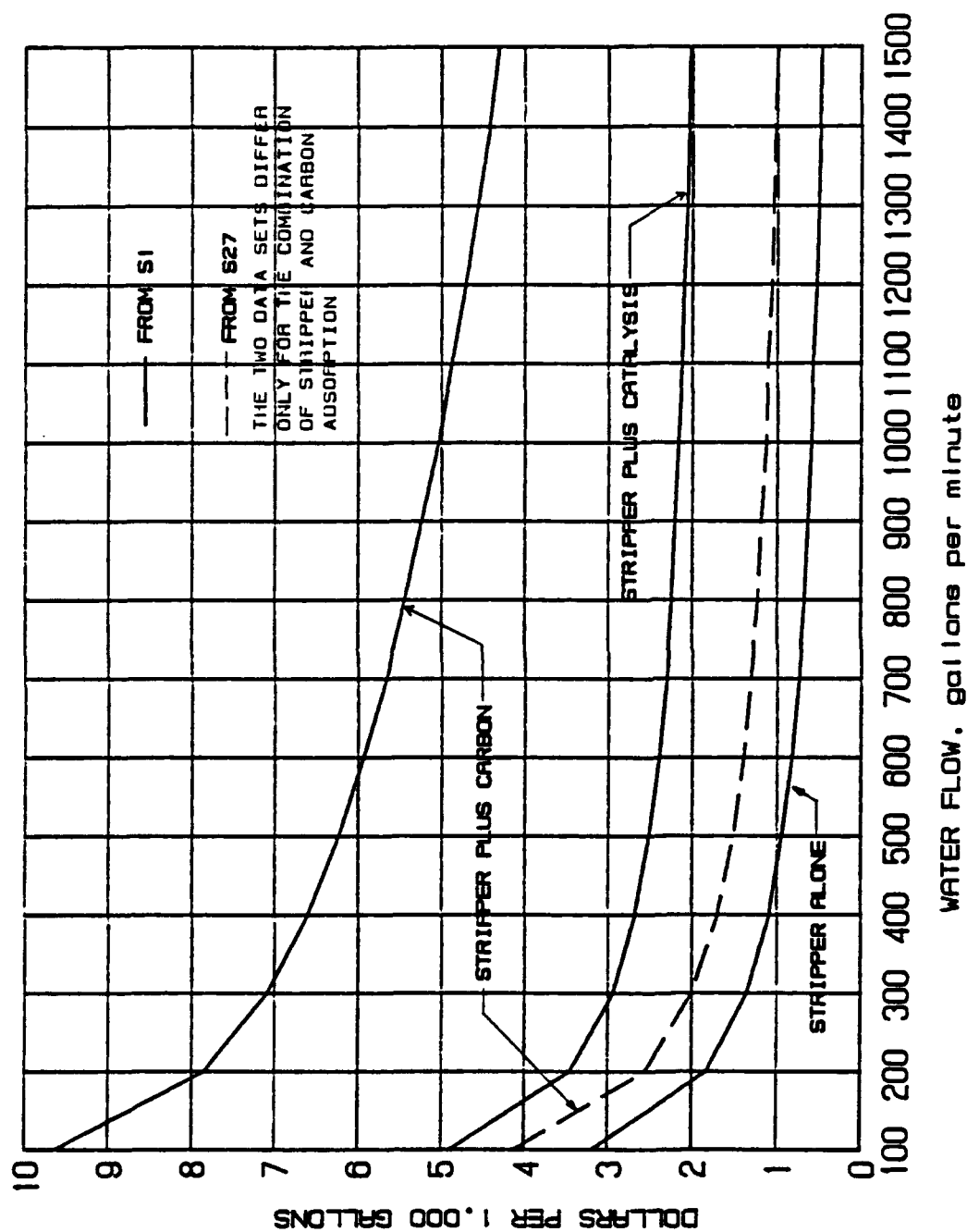


Figure 87. Comparison of Lifetime Processing Costs vs Capacity for Two Groundwater Contamination levels for an Air Stripping System Featuring Traditional Packed Towers for Removal of Benzene from Groundwater. The Two Groundwater Concentrations are 10 ppm (Method A-1) and 0.1 ppm (Method A-2).

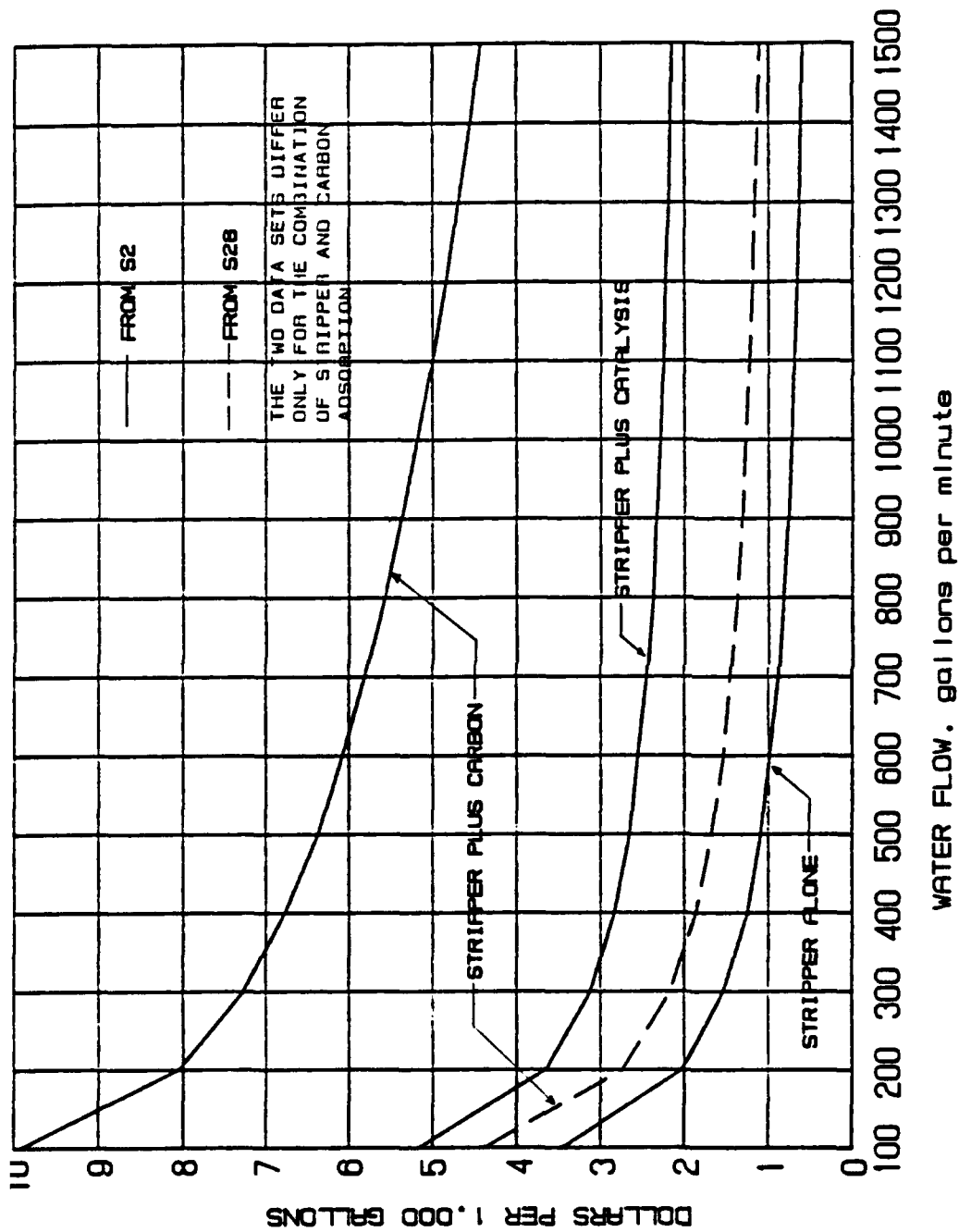


Figure 88. Comparison of Lifetime Processing Costs vs. Capacity for Two Groundwater Contamination Levels for an Air Stripping System Featuring Rotary Air Strippers for Removal of Benzene from Groundwater. The Two Groundwater Concentrations are 10 ppm (Method A-1) and 0.1 ppm (Method A-2).

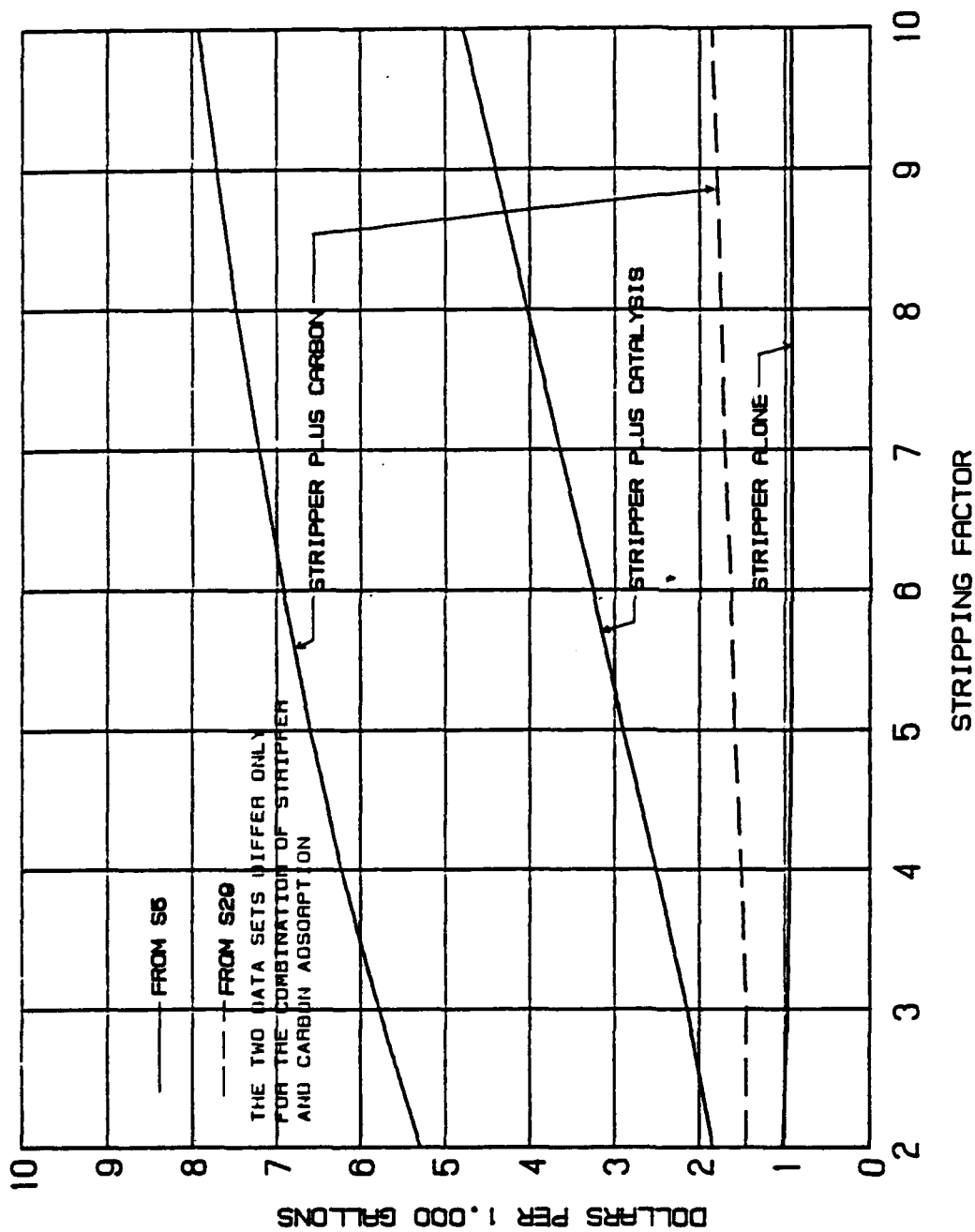


Figure 89. Comparison of Lifetime Processing Costs vs. Stripping Factor for Two Groundwater Contamination Levels for an Air Stripping System Featuring Traditional Packed Towers for Removal of Benzene from Groundwater. The Two Groundwater Concentrations are 10 ppm (Method A-1) and 0.1 ppm (Method A-2).

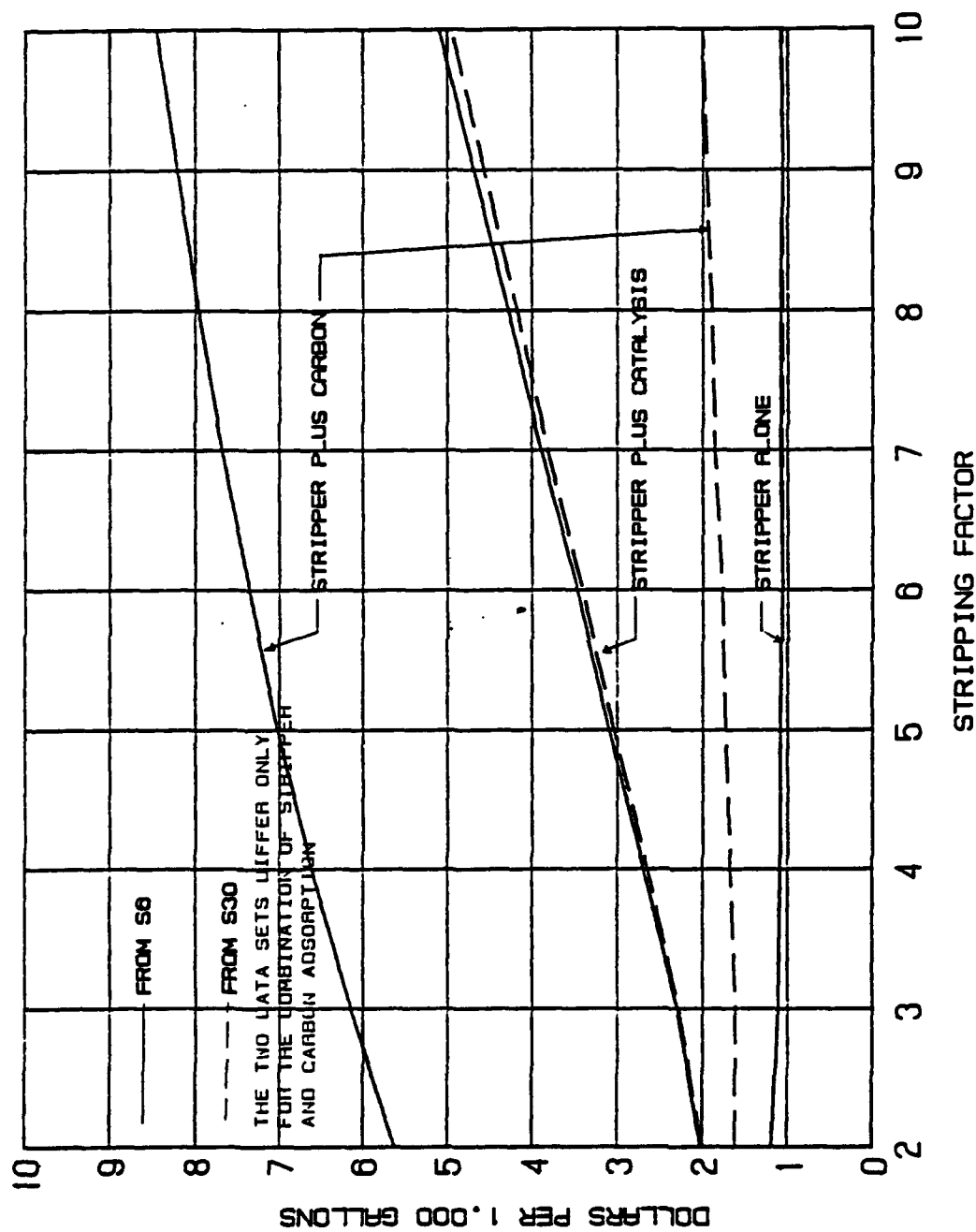


Figure 90. Comparison of Lifetime Processing Costs vs. Stripping Factor for Two Groundwater Contamination Levels for an Air Stripping System Featuring a Rotary Air Stripper for Removal of Benzene from Groundwater. The Two Groundwater Concentrations are 10 ppm (Method A-1) and 0.1 ppm (Method A-2).

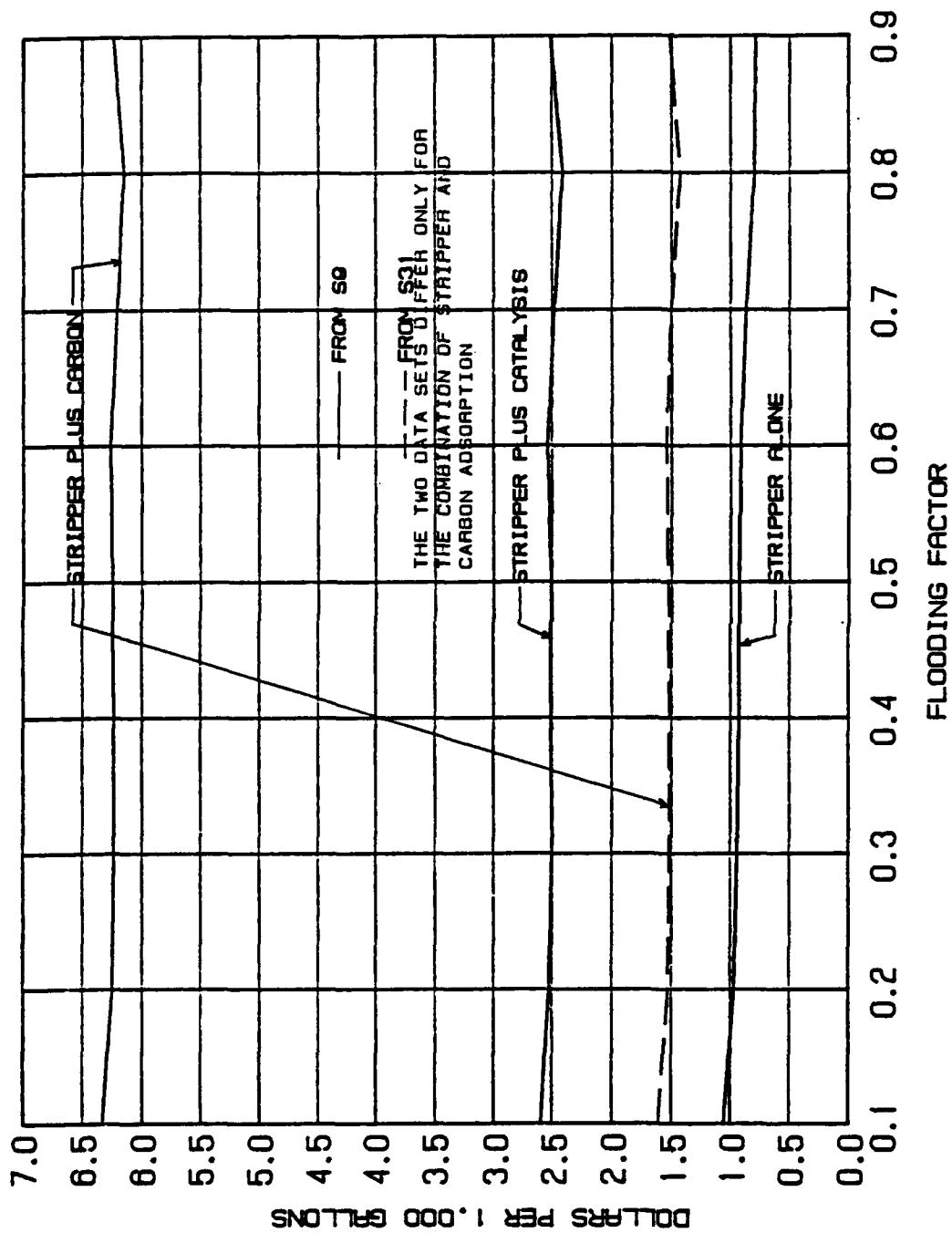


Figure 91. Comparison of Lifetime Processing Costs vs. Flooding Factor for Two Groundwater Contamination Levels for an Air Stripping System Featuring Traditional Packed Towers for Removal of Benzene from Groundwater. The Two Groundwater Concentrations are 10 ppm (Method A-1) and 0.1 ppm (Method A-2).

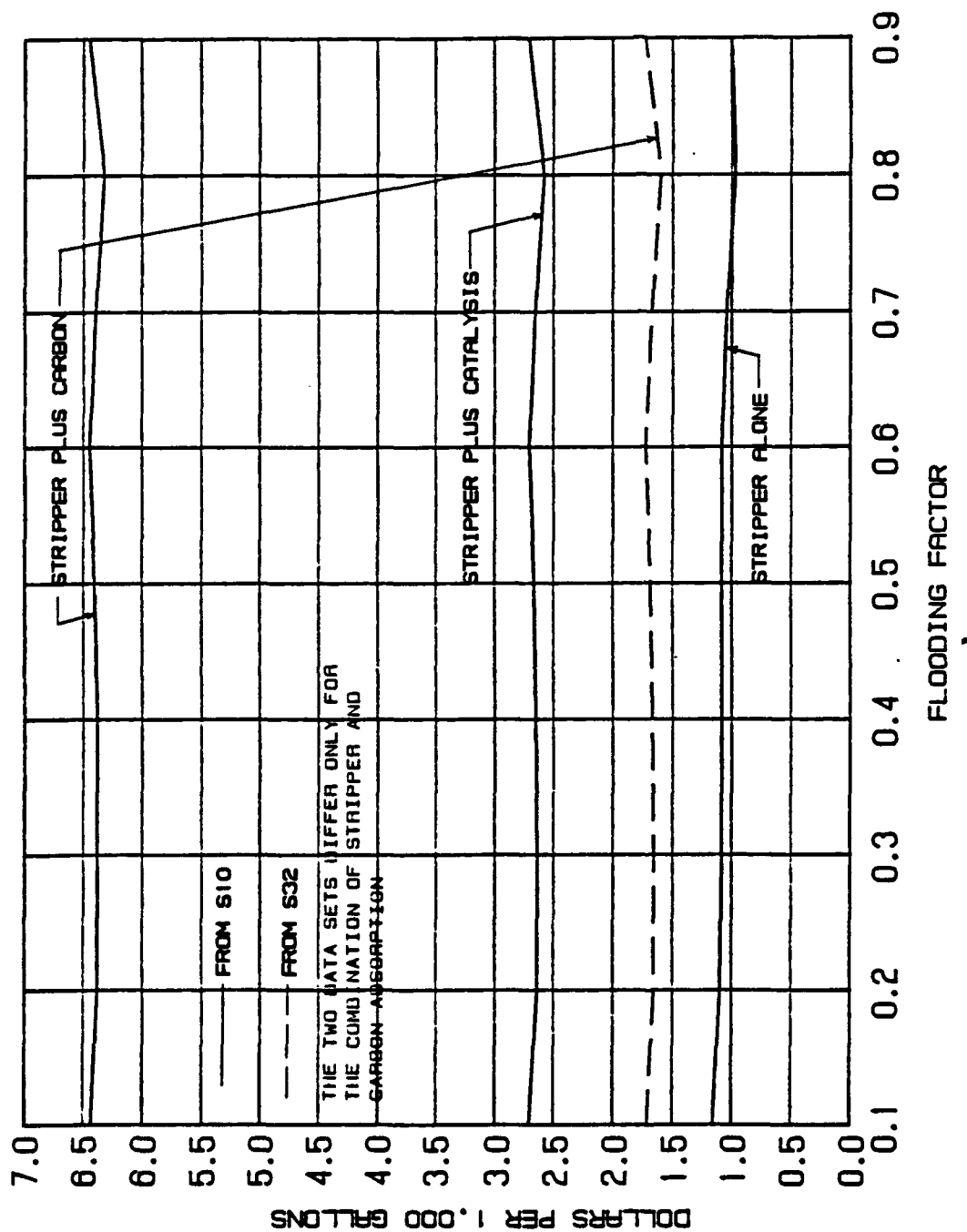


Figure 92. Comparison of Lifetime Processing Costs vs. Flooding Factor for Two Groundwater Contamination Levels for an Air Stripping System Featuring a Rotary Air Stripper for Removal of Benzene from Groundwater. The Two Groundwater Contamination Levels are 10 ppm (Method A-1) and 0.1 ppm (Method A-2).



The key observation from the data in this group is that the change in concentration affects costs only for the carbon adsorption unit for cleanup of the off gas. This should not be a surprise. The cost estimating for the catalytic incineration unit is based upon air flow rates rather than contaminant concentration. The sizing and thus the costs for the stripper are based primarily upon physical operating conditions rather than upon the contaminant concentration.

The cost estimation methods (A-2) for this group are the same as for all preceding groups, and as used in the design spreadsheet VOC-2.100. For the remaining data analysis groups in this chapter, cost estimating methods taken from an EPA sponsored study were used to generate some comparative information related to the cost estimating itself.

### **3. Method-B Results**

#### **a. Group VI, B-1 and B-2**

Figures 93-98 present processing costs per 1000 gallons of groundwater, based upon cost estimates using the EPA sponsored study methods (45). In each of the six graphs, comparison cost curves taken from the earlier methods indicated by COT are included for direct comparison.

Figures 93-95 deal with TCE as the contaminant and a concentration level of 10 ppm (B-1). Figures 96-98 deal with benzene as the contaminant and a concentration level of 0.100 ppm (B-2). A packed stripper is used in all six cases. Except for these variations, the base case conditions are those shown earlier in Table 26.

For all six cases shown in the graphs in Figures 93 through 98, the deviation on the average of the two cost estimating methods is less than the probable uncertainty of 30 percent in the cost estimating for either of the two methods. At this level of probable accuracy, one cannot distinguish between the two cost estimating methods A and B.

Overhead handling is the primary difference between the two cost estimating methods as used here. Method A is the simpler and more flexible of the two methods. In Method A, it is possible to handle the overhead as a single variable, and thus to readily examine the impact of variations in the overhead rate. In Method B, the overhead is broken out into several categories, making it more complex to evaluate.

The general overhead issue and methods of "overhead accounting" are highly variable throughout both the private and public sectors. Thus alternatives to either of the two methods used here may readily be found.

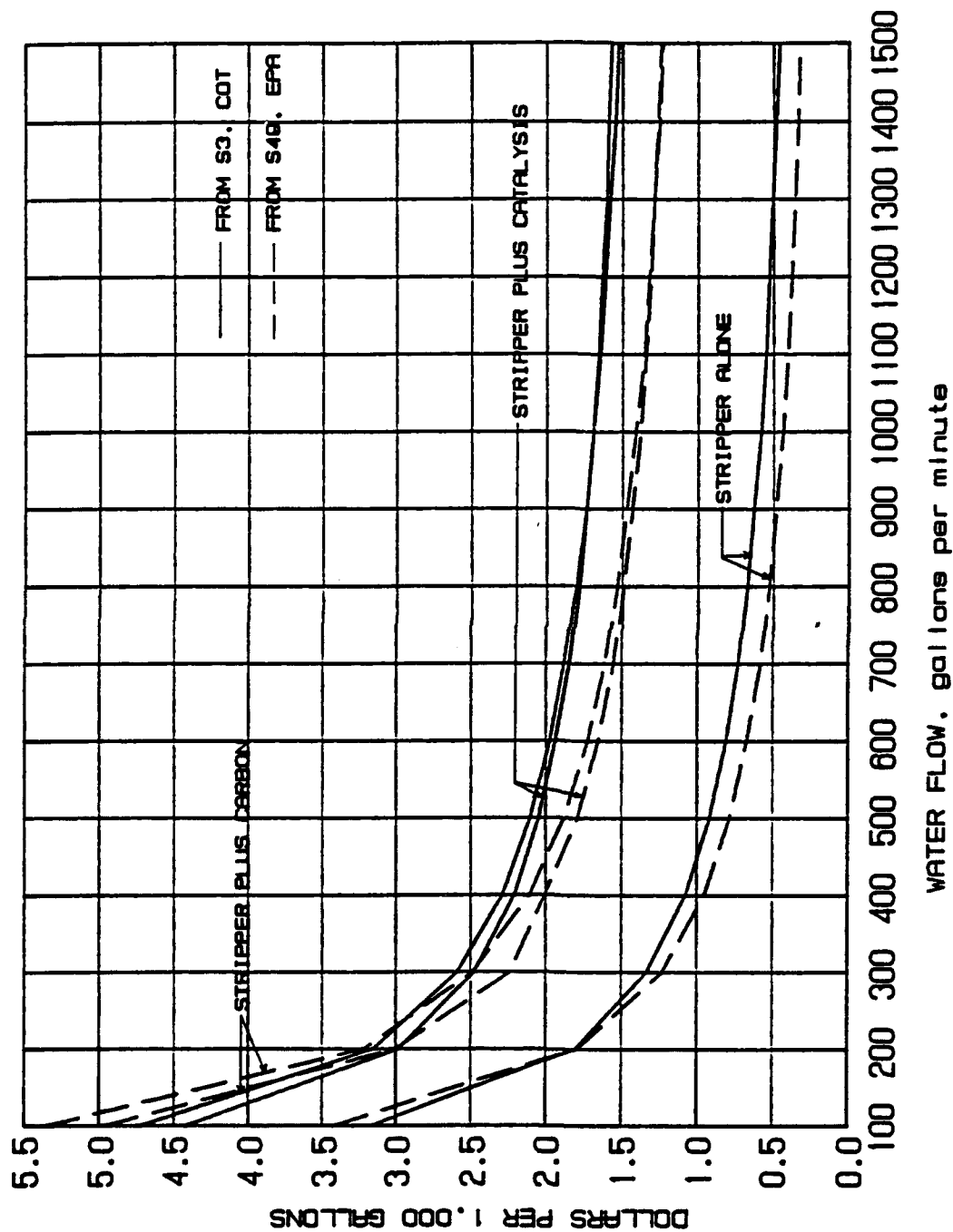


Figure 93. Comparison of Lifetime Processing Costs vs Capacity for Methods A-1 and B-1 for an Air Stripping System Featuring Traditional packed Towers for Removal of TCE from Groundwater.

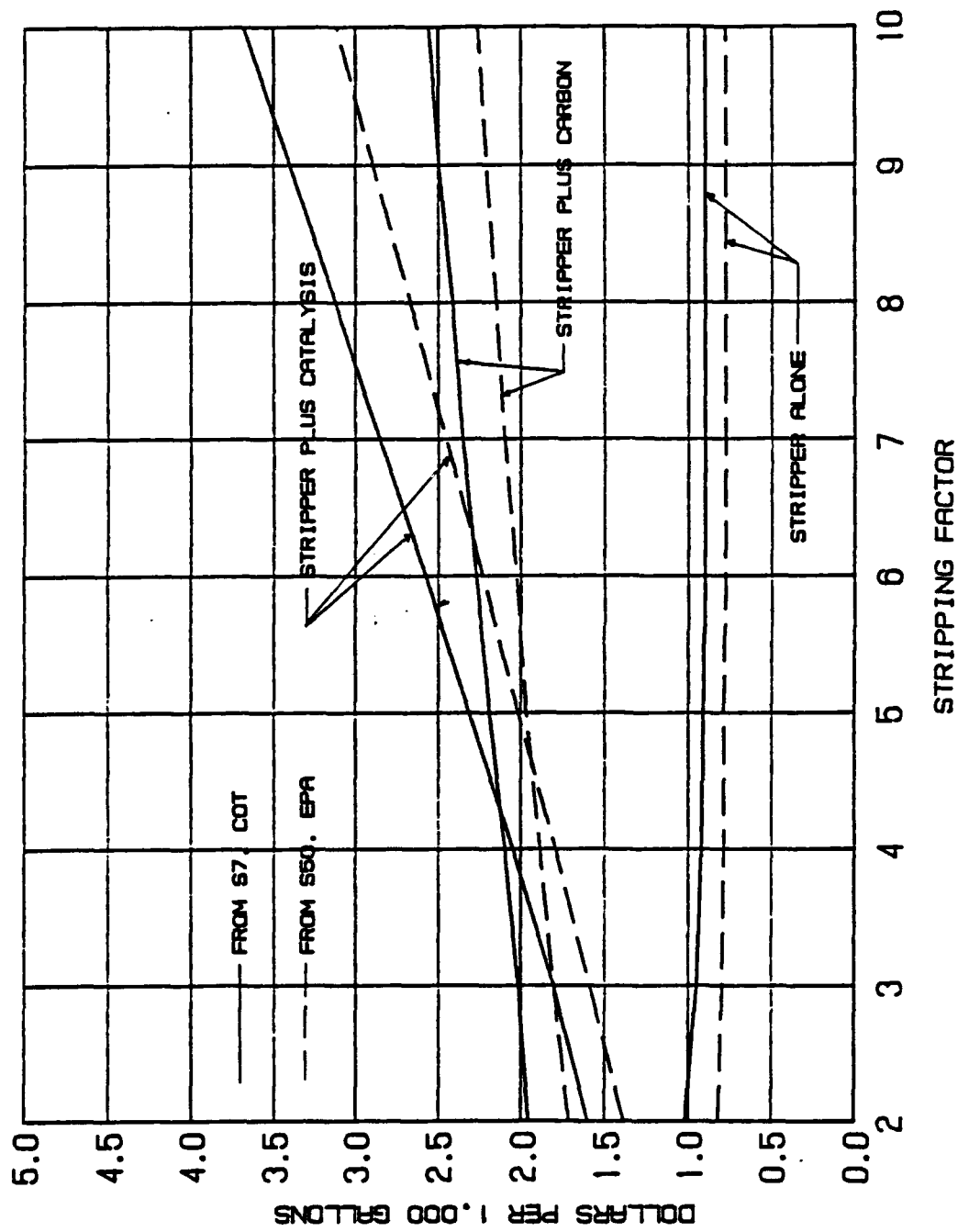


Figure 94. Comparison of Lifetime Processing Costs vs. Stripping Factor for Method A-1 and B-1 for an Air Stripping System Featuring Traditional Packed Towers for Removal of TCE from Groundwater.

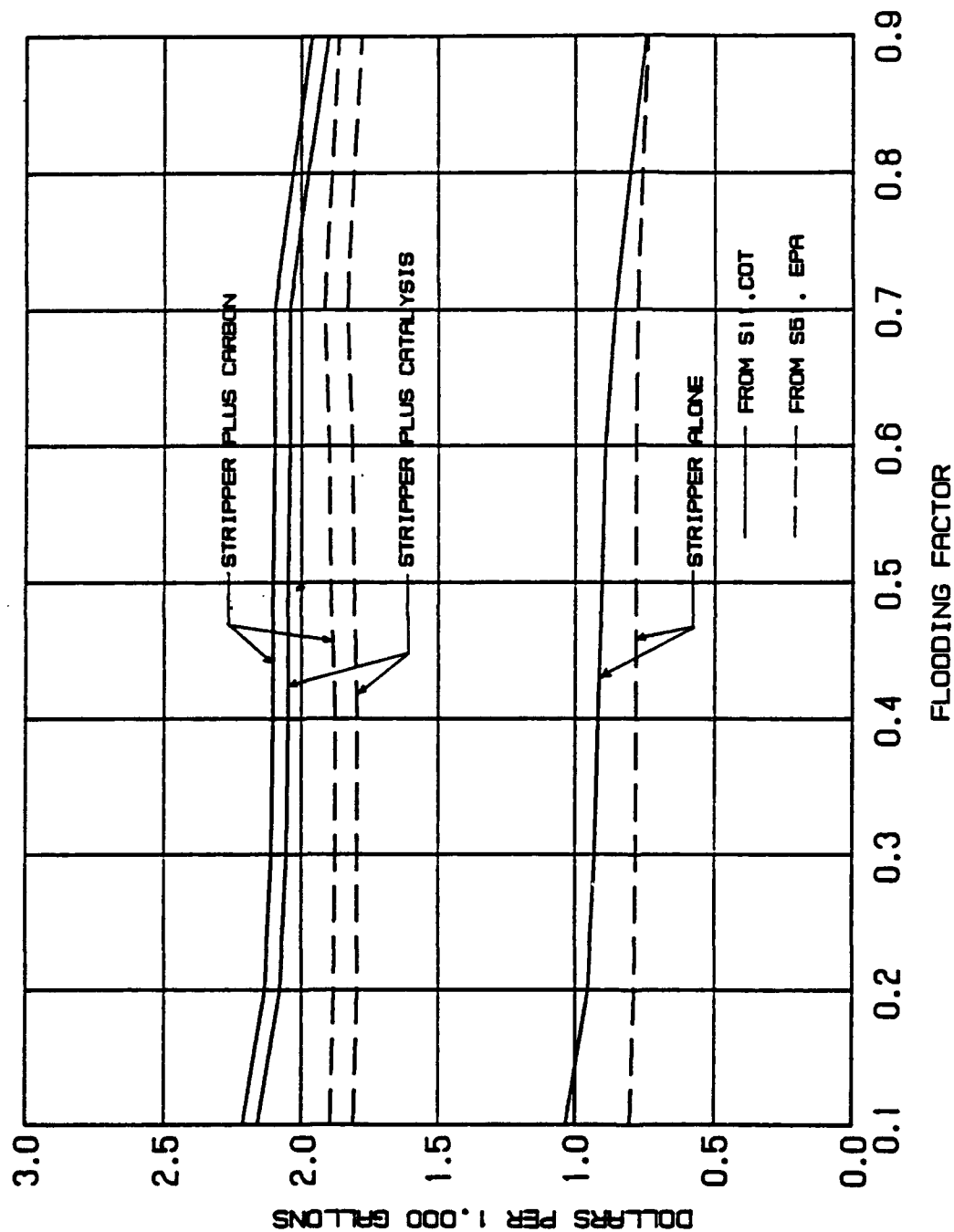


Figure 95. Analysis of Lifetime Processing Costs vs. Flooding Factor Illustrating Two Different Cost Estimating Procedures, Methods A-1 and B-1, for an Air Stripping System Featuring a Traditional Packed Tower for Removal of TCE from Groundwater.

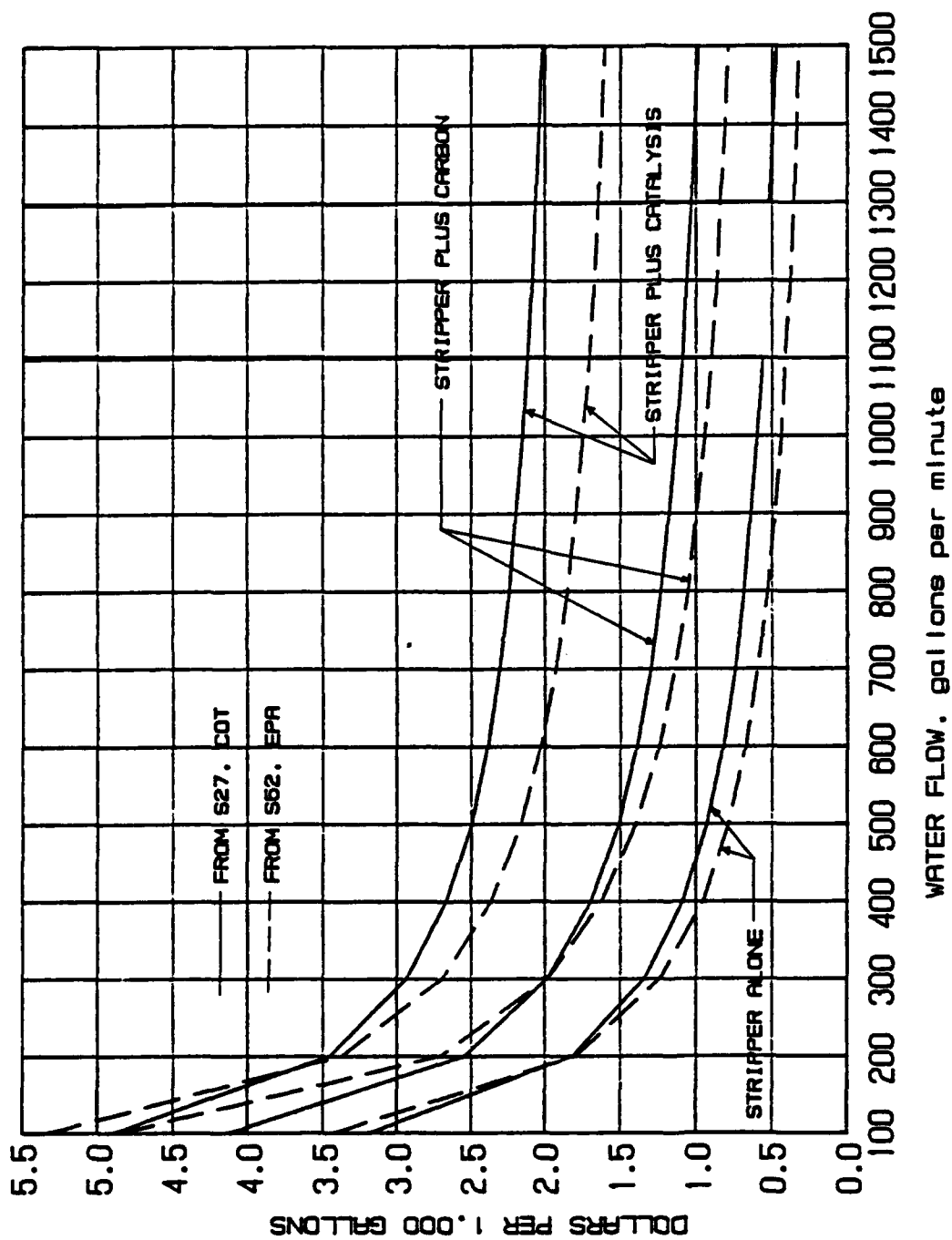


Figure 96. Comparison of Lifetime Processing Costs vs. Capacity Illustrating Two Different Cost Estimating Procedures, Methods A-2 and B-2, for an Air Stripping System Featuring a Traditional Packed Tower for Benzene Removal from Groundwater.

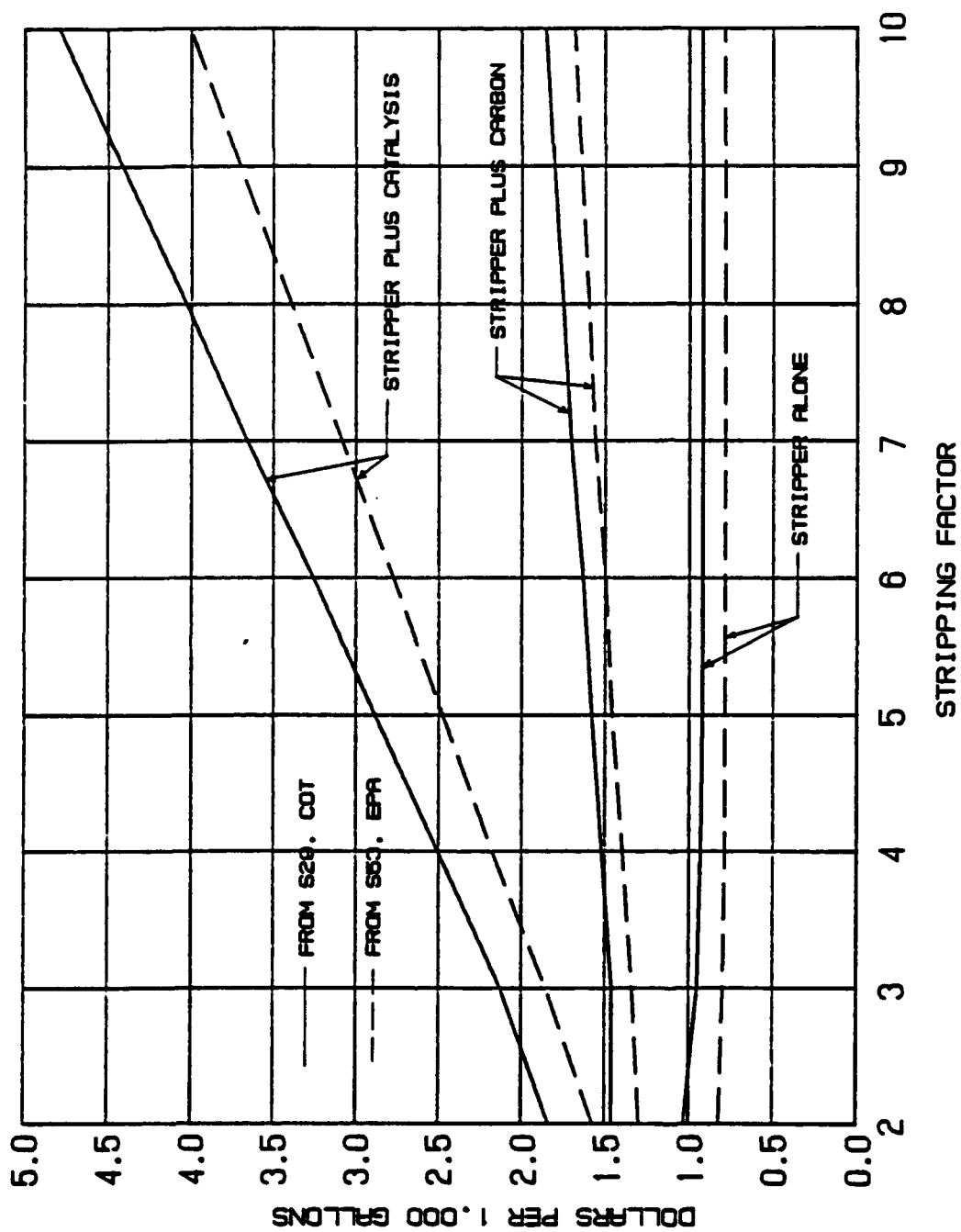


Figure 97. Comparison of Lifetime Processing Costs vs. Stripping Factor Illustrating Two Different Cost Estimating Procedures, Methods A-2 and B-2, for an Air Stripping System Featuring a Traditional Packed Tower for Removal of Benzene from Groundwater.

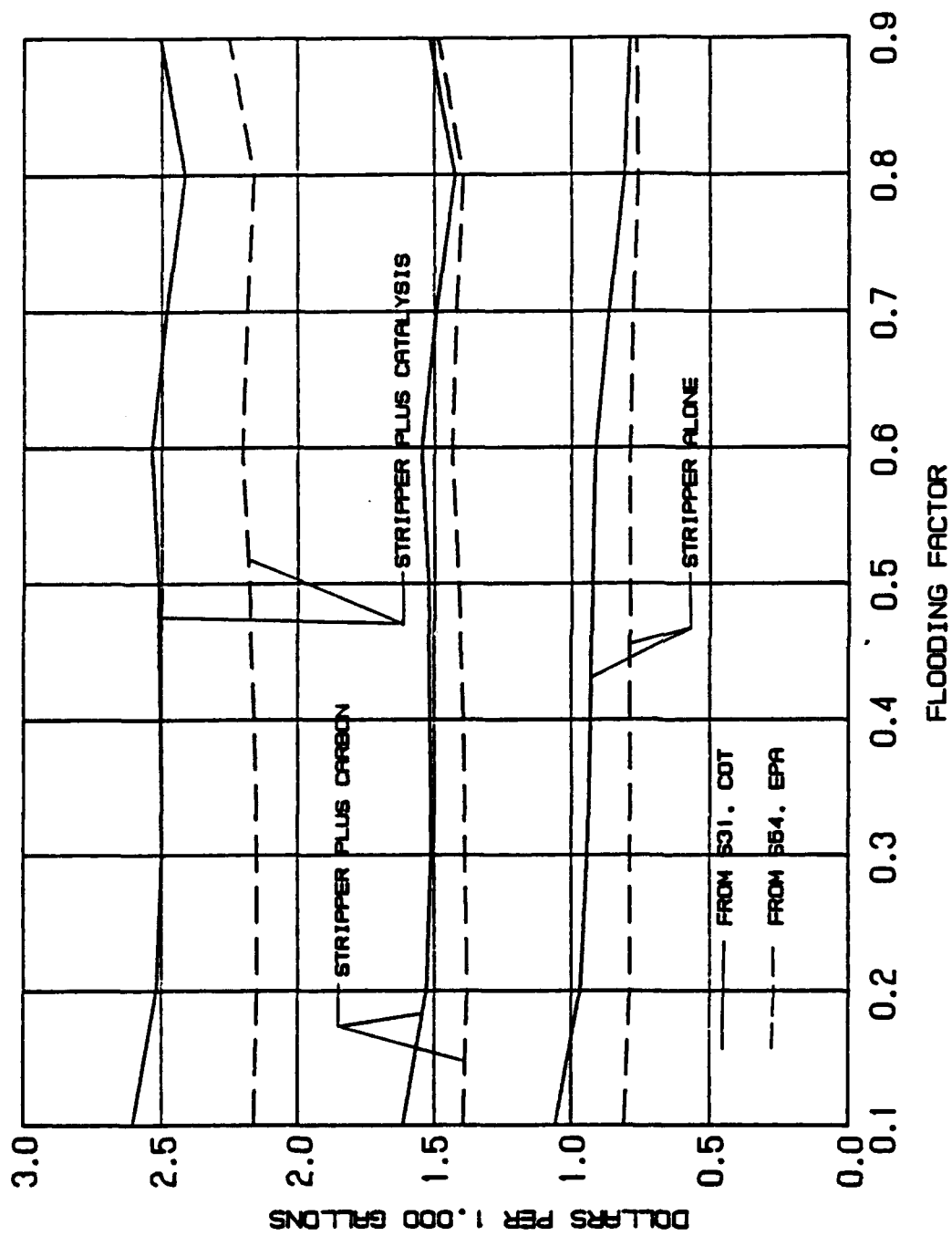


Figure 98. Comparison of Lifetime Costs vs. Flooding Factor Illustrating Two Different Cost Estimating Procedures, Methods A-2 and B-2, for an Air Stripping System Featuring a Traditional Packed Tower for Removal of Benzene from Groundwater.

At the level of overall accuracy likely to be obtained in a study of this type, the more useful analytical strategy appears to be that of treating individual cost items as single rather than as multiple variables. This strategy simplifies the analysis without sacrifice of accuracy, and also allows single or multivariant sensitivity analyses to be carried out more easily. Because of that, Method A (spreadsheet VOC-2.100), appears to be the more useful of the two methods evaluated.

#### **G. SUMMARY**

Spreadsheet software has been developed for purposes of generating design outputs, estimates of fixed capital and of annual expense costs in 1990 dollars, and analysis of operating lifetime processing costs per 1000 gallons of groundwater treated. The six design cases considered include packed column and centrifugal strippers, strippers plus carbon adsorption cleanup of off gas, and strippers plus catalytic incineration cleanup of off gas.

Approximately 30 input variables may be examined for their impact on the cost performance of these systems. The data also include analyses for TCE (trichloroethylene) and for benzene (as a component of a hypothetical jet fuel). Cost performance data within this chapter are presented as a series of graphs providing single variable sensitivity analyses. Supplemental details are provided in the Appendices A, B, and C of this report.



## SECTION VIII

### CONCLUSIONS

#### A. OVERALL CONCLUSIONS

The operation of the experimental system was as planned; no problems arose that could not be corrected in the field. Data acquisition, analysis, and reduction techniques worked well. Accumulation of precipitate in both the traditional packed tower and rotary stripper, as well as the supply lines, were identified as major problems for continuous operation. The occurrence of foaming of the groundwater was noted in the traditional packed tower; this phenomena is likely to be site specific and results in a higher pressure drop across the tower than would be expected for air-water service. The mechanical operation and data generation of the emission control equipment was acceptable. The activated carbon beds provided acceptable control of the target species; substantial quantities of other species, possibly lighter hydrocarbons, were not effectively removed by the activated carbon. The catalysts used in the incinerator tests lost activity almost immediately; this loss of activity was attributed to sulfur poisoning. The synthetic adsorbents tested did not provide adequate emission control; in one case, this is likely to be due to the material having a smaller pore size than anticipated, and in the other case an inadequate bed depth may have been used.

#### B. TRADITIONAL PACKED TOWER

##### 1. Flexirings®

Hydraulic tests indicated that the pressure drop was higher for groundwater than for process water; this difference was attributed to foaming of the groundwater.

No significant effects on the experimental  $H_{OL}$  were observed for liquid rates ranging from 5.2 to 16.5 kg/m<sup>2</sup>-second and stripping factors (based on m-xylene) from 1.04 to 3.76. The  $H_{OL}$  data from groundwater tests compared well with that from tests utilizing synthetic solutions made from process water. All the experimental  $H_{OL}$  data compared very well with predictions based on the correlations by Onda et al. (Reference 15);  $H_{OL}$  predictions based on correlations by Bolles and Fair (Reference 12) tended to over-predict the experimental data.

##### 2. Koch/Sulzer-Type BX Packing

For liquid loadings of 1.4 to 16.3 kg/m<sup>2</sup>-second and stripping factors of 0.88 to 4.83, the experimental  $H_{OL}$  showed a strong dependance on the liquid rate and no significant effect of the stripping factor. A model for the liquid-phase mass transfer phenomena was developed; predictions of  $H_{OL}$  using this model coupled with existing models for gas-phase mass transfer phenomena, agreed

well with the experimental  $H_{iOL}$  values. In general, the  $H_{iOL}$  values for the Koch/Sulzer packings were about 60 percent of those of the 16-mm Flexirings®. The  $H_{iOL}$  values show a strong proportionality to the liquid loading rate that is not generally observed with random packings.

### 3. Koch Flexiramic® Packing

For liquid loadings of 1.6 to 16.7 kg/m<sup>2</sup>-second and stripping factors (based on m-xylene) of 0.87 to 4.32, some effects of both loading and stripping factor on  $H_{iOL}$  were noted. A model for the liquid-phase mass-transfer phenomena was developed; predictions of  $H_{iOL}$  using this model coupled with an existing model for the gas-phase mass transfer phenomena, agreed well with the experimental data. In general, the  $H_{iOL}$  values were similar to those using the 16-mm Flexirings®; however, the strong dependency of  $H_{iOL}$  on the liquid rate is not generally observed with random packings.

### 4. Delta SH Packing

For liquid loadings of 5.3 to 27.5 kg/m<sup>2</sup>-second and at considerably higher stripping factors than had been previously used, effects of both liquid rate and stripping factor on experimental  $H_{iOL}$  values (after correction for stripping occurring at the spray distributor) were observed.

## C. ROTARY AIR STRIPPER

Hydraulic test data indicated that the Sherwood flooding correlation underestimates the lower limit of operability for the rotational speed. In the region where the rotor speed is greater than the lower limit of operability, an empirical equation was developed for the estimation of the pressure drop.

Mass transfer concepts of  $N_{iOL}$  and  $H_{iOL}$  for conventional packed towers can be adopted to the centrifugal vapor-liquid contactor by deriving the equations in polar coordinates. The equation for the  $N_{iOL}$  remains unchanged, while an  $A_{iOL}$  concept is more appropriate than the  $H_{iOL}$ . The  $A_{iOL}$  appeared to be more dependent upon the specific surface area of the packing than the rotor speed and liquid flow rate under the conditions used in this study. A new correlation for predicting  $A_{iOL}$  based on the specific surface area of the packing was developed which describes the experimental data with a reasonable degree of accuracy.

The power requirement of a centrifugal vapor-liquid contactor is mainly a function of the liquid flow rate, outer radius of the packing torus, and rotor speed. A correlation based on the power required to accelerate the liquid was developed; this correlation satisfactorily predicted the power consumption at the experimental conditions.

The previous claims in the literature that the centrifugal vapor-liquid contactor is not susceptible to fouling of the packing because of high shear forces were found not to be valid. Preliminary signs

of plugging due to mineral deposition were observed in two of the rotors and the third rotor experienced high pressure drops due to plugging after a very short operating time. It should be emphasized that the groundwater at Eglin Air Force Base has very high content (9 ppm) of iron and may not be a fair evaluation of the machine.

#### **D. EMISSION CONTROL BY CATALYTIC INCINERATION**

The activity of the noble metal catalyst was lost before any useful abatement results were obtained. This loss in activity was attributed to sulfur poisoning. Levels of several hundred parts per billion of sulfur in the groundwater were measured.

#### **E. EMISSION CONTROL BY ACTIVATED CARBON ADSORPTION**

Control of emissions by activated carbon was achieved. Of the observed target hydrocarbon species, the first to break through was methyl cyclohexane, followed closely by benzene. The effect of humidity on loading was as expected, with greater loadings achieved at low humidity. Significant quantities of presumably lighter hydrocarbon species than the target compounds were noted in the stripper effluent; these were not effectively adsorbed by the carbon.

#### **F. EMISSION CONTROL BY MOLECULAR SIEVES**

No generally useful results were obtained. A portion of the experiments was done with material having pore sizes that appear to be too small for this application. Later experiments involved larger pore size material; however, the lack of adequate bed depth was likely responsible for the poor results.

#### **G. ECONOMIC ANALYSIS**

Analysis of the lifetime operating costs for application of air stripping technology for remediation of contaminated groundwater indicates the following: (1) little cost differences are observable for the use of a traditional packed tower compared to a rotary air stripper; as more experience is accumulated with rotary air strippers, better estimates may allow discrimination between operating costs of these two technologies, (2) the use of emission control devices for systems for air stripping of VOCs from groundwater considerably increases the costs of such operations. Comparison of the cost of emission control for options of catalytic incineration vs activated carbon adsorption are strongly related to the concentration of contaminants in the groundwater; the carbon requirements will vary proportional to this contaminant concentration, (3) cost considerations favor the use of lower values of the stripping factor, and (4) the costs of the remediation of contaminated groundwater with and without emissions control are largely controlled by operating, rather than capital costs.

## SECTION IX

### RECOMMENDATIONS

Air strippers for VOC removal from groundwater may be designed based on existing techniques for Flexiring® packing and techniques developed in this activity for Koch/Sulzer and Koch Flexiramic® packings and the HIGEE contactor. Operational problems of precipitate accumulation and foaming of the groundwater should be considered in the design and operating procedures for air strippers. For foaming liquids, packed tower operations with random packings are usually accomplished, as in these tests, by utilizing reduced liquid loads; the use of structured packings such as those used in these tests should be very useful for foaming liquids without reducing liquid rates.

The selection of emission control devices for applications such as those of this study remains a troublesome issue. The failure of activated carbon to remove some unidentified hydrocarbon species in the air stripper effluent is bothersome. The rapid loss of catalytic activity would likely preclude the use of such devices for situations similar to those of this study and will require careful study for other applications. The use of molecular sieve material is desirable if field regeneration procedures are available, but will require further study for the proper selection and operation of such systems.

. In summary, the remaining issues for design and operation of air strippers appear to be primarily operational. Providing effective emission control for conditions similar to those of this study will require further study.

## SECTION X

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## APPENDIX A

### DESIGN AND COST ESTIMATING SPREADSHEET

#### VOC-2.100

The following 26 tables make up spreadsheet VOC-2.100, which is written in MULTIPLAN 2.01. The file may be exported upward into MP 3.0 or MP 4.0 without difficulty. Tables A-1 through A-12 deal with the design parameters of a packed column, a carbon adsorption off-gas treatment system, and a catalytic incineration off-gas treatment system. These 12 tables simultaneously handle TCE and also benzene as a marker for jet fuel. The seven tables A-D1B through A-D7B are sensitivity analysis output summaries for the Benzene case, and the seven tables A-D1T through A-D7T are the same for the TCE case. A-D1B and A-D2B along with A-D1T and A-D2T summarize requisite design information for use in single-variant sensitivity analyses. Tables A-D3B through A-D5B and A-D3T through A-D5T summarize the fixed capital and the annual expense cost estimates for the packed column stripper, the carbon adsorption off-gas treatment, and the catalytic incineration off-gas treatment. A-D6B and A-D6T consolidate the fixed capital and the annual expense cost estimates for the packed column stripper options. A-D7B and A-D7T consolidate these for the rotary stripper option.

Fixed capital and annual expense (non-capital) cost estimates are adjusted to 1990 dollars in the following tables. Continuing inflation adjustments for the period of the operating lifetime are handled in a separate spreadsheet, VOC-2.300, which is included as the following Appendix B. Further details will be found in the related body of the text, as well as in a separate "user/operator manual" for the spreadsheet.

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[TAB1]  
VOC-2.100

TABLE A-1  
DESIGN INPUT TABLE  
Independent Design Variable Inputs

NOTE: All independent variable input names/locations indicated as +[ ]

GENERAL INPUTS	[NAME]	VALUE	ELECTRICAL EFFICIENCIES	[NAME]	VALUE
Operating Temperature, F	+{TF}	60	Air Heaters	+{EFFH}	0.7
Inlet Gas Pressure	+{PAT}	1.00	Air Blowers	+{EFFA}	0.6
			Water Pumps	+{EFFW}	0.7
GROUNDWATER STREAM					
Water Feed Rate, Gallons/Minute	+{WGM}	500	STRIPPER RELATED PARAMETERS		
Contaminant Concentration, ppb IN	+{PPBI}	100	Groundwater Depth, ft +{HGW}	+{HGW}	30
Contaminant Cleanup Factor	+{CUF}	0.990	Fanning Friction Factor+{F}	+{F}	0.008
			Horizontal Pipe Length, ft	+{HPL}	100
			Consolidated Friction Loss Coefficient		
			for valves, elbows, etc.	+{Kf}	15
STRIPPER					
Stripping Factor (greater than unity)	+{S}	4.0	CARBON AIR STREAM CLEANUP		
Packing Factor (Treybal, 3rd Ed.)			Carbon Recycle Interval, days	+{CRI}	75
For Size: mm(in)---METAL PALL RINGS ONLY			Carbon Use Safety Factor	+{CSF}	1.5
Size--> 16(5/8) 25(1) 38(1 1/2) 50(2)			Carbon Bulk Density, lb/ft <sup>3</sup>	+{CD}	30
Select Cf--> 70 48 28 20			Freundlich Adjustment Factor	+{FAF}	0.20108
			(For BENZENE ONLY)		
Packing Size, mm (in)	+{SIZE}	50(2)	CATALYTIC INCINERATION AIR STREAM CLEAN UP		
Packing Factor	+{Cf}	20	Catalytic Unit Size Safety Factor	+{CASF}	1.5
Correlation factor term *	+{J}	1.502			
Flooding Factor	+{FF}	0.4			
Height of Each Packed Bed, ft	+{HPB}	10			
Height Design Safety Factor	+{SF}	1.7	OVERALL OPERATING CYCLE LOAD FACTOR	+{LF}	0.85
			[365 days/year = 1.00]		
* See Treybal, 3rd Ed.					
SINGLE VARIABLE SENSITIVITY ANALYSIS, INPUT CONTROLS					
[To suppress sensitivity iterations, set VNUM = 0]					
Name of variable	+{VI}		Equip. Inst. Factor (Stripper)	+{EIPS}	2.20
Variable initial value	+{VIN}		EIF (Carbon, and Catalytic)	+{EIFC}	1.60
Variable step value	+{VSTEP}		Materials (SS) Factor, STRIPPER	+{MMF}	1.70
Number of values to run	+{VNUM}		Fuel Oil, 1990 \$/MMBTU	+{FC}	6.15
Current variable value	[VAR]		Electricity Cost, 1990 \$/kwh	+{EC}	0.060
			Operations & Maintenance Factor	+{OM}	0.150
			Overhead Rate (%) on Expense	+{OHR}	100
			Av. Annual Inflation: 1977-90	+{I}	0.0484

COST PARAMETERS

VOC-2: 100

```
+{ } Indicates original location of a NAMED INDEPENDENT VARIABLE input (see Table 1).
( ) Indicates original location of a NAMED DEPENDENT VARIABLE.
{ } Indicates a NAMED VALUE, transferred from an earlier location.
```

GENERAL INPUTS			(NAME)	VALUE	--ELECTRICAL EFFICIENCIES	(NAME)	VALUE
Operating Temperature, F	Fahrenheit		(TF)	60	Air Heaters	{EFFH}	0.7
	Rankine		(TR)	519.670	Air Blowers	{EFFB}	0.6
	Celsius		(TC)	15.556	Water Pumps	{EFFW}	0.7
	Kelvin		(TK)	288.706			
Inlet Gas Pressure	Atmospheres		(PAT)	1.00	--STRIPPER RELATED PARAMETERS		
					Groundwater Depth, ft	(HGW)	30
					Fanning Friction Factor	(F)	0.008
					Horizontal Pipe Length, ft	(HPL)	100
					Pipe Internal Diameter, inches	(PDIN)	7
					Consolidated Friction Loss Coefficient for valves, elbows, etc.	{Kf}	15
					--CARBON AIR STREAM CLEANUP		
					Carbon Recycle Interval, days	{CRI}	75
					Carbon Use Safety Factor	{CSF}	1.5
					Carbon Bulk Density, lb/ft <sup>3</sup>	{CD}	30
					Freundlich Factor, BENZENE	{FAF}	0.20108
					--CATALYTIC INCINERATION AIR STREAM CLEAN UP		
					Catalytic Unit Size Safety Factor {CASF}		1.5
					--OVERALL OPERATING LOAD FACTOR		
					{365 days/year = 1.00}	{LF}	0.85
					--COST PARAMETERS		
					Fuel Oil, 1990 \$/MBTU	{FC}	6.15
					Equip. Inst. Factor {Stripper}	{EIFS}	2.20
					EIF {Carbon, and Catalytic}	{EIFC}	1.60
					Materials {SS} Factor, STRIPPER	{MMF}	1.70
					Plastic Pall Rings, 1990\$/ft <sup>3</sup>	{PC}	5.50
					Electricity Cost, 1990 \$/kwh	{EC}	0.060
					Operations & Maintenance Factor	{OM}	0.150
					Overhead Rate (%) on Expense	{OHR}	100
					Av. Annual Inflation: 1977-90	{I}	0.0484
					TCE*		
					BENZENE		
					{MWA}	28.96	
					{MWV}	18.016	
					{MWR}	78.11	
					{GSA}	3.217E+01	
					{GCM}	1.158E+05	
					{GCH}	4.170E+08	
					Sensitivity Analysis Running		YES
					Name of Variable		CRI

\* Trichloroethylene

BENZENE TCE\*  
=====

MISCELLANEOUS

Water Viscosity, Centipoise (in TC) [WV1] 1.12171 1.12171  
Water Viscosity, lb/ft s [WV2] 7.538E-04 7.538E-04

Air Viscosity, Centipoise (in TF) [AV1] 0.01736 0.01736  
Air Viscosity, lb/ft s [AV2] 1.167E-05 1.167E-05

Henry's Law Constants [H] 198.293 276.118  
[Dimensionless, i.e.  $H = y/x$ , or the ratio  
of the mole fractions in the gas & liquid phases]

TEMPERATURES

Operating Temperature, F {TF} 60 60  
Operating Temperature, C {TC} 15.556 15.556  
Operating Temperature, R {TR} 519.670 519.670  
Operating Temperature, K {TK} 288.706 288.706

WATER FEED DATA, All Calculated from [WGM] input.

Water Feed Rate, Gallons/Minute {WGM} 500 500  
Water Feed Rate, Cubic Feet/Minute [WCFM] 66.8405 66.8405  
Water Density, Pounds/Cubic Foot [WD] 62.3582 62.3582  
Water Feed Rate, Pounds/Minute [WPM] 4168.0479 4168.0479  
Water Feed Rate, Pound Moles/Minute [WPMU] 231.3526 231.3526

AIR FEED DATA

Air Pressure, Atm {PAT} 1.000 1.000  
Air Pound Moles/Cubic Foot \*\*\* [AMCF] 0.002635 0.002635  
Air Pounds/Cubic Foot, DENSITY \*\*\* [AD] 0.076311 0.076311  
And introduce Henry's Constant & Stripping Factor  
Air Pound Moles/Minute (makes use of S) [APMU] 4.6669 3.3515  
Air Pounds/Minute [APM] 135.1526 97.0594  
Air Cubic Feet/Minute [ACFM] 1771.0661 1271.8857  
Mass Ratio: Water/Air [MASSR] 30.8396 42.9433  
Mole Ratio: Water/Air [MOLER] 49.5734 69.0296

\*\*\* Corrected for pressure [PAT] and temperature [TF], but  
NOT humidity corrected, i.e. for moisture content of air.

[TAB4] TABLE A-4  
VOC-2.100 DIAMETER CALCULATIONS FOR PACKED STRIPPER

CALCULATE THE TREYBAL ABSCISSA = (WPM/APM)*(AD/WD) <sup>0.5</sup>				
Abscissa, [ABSB], and [ABST]	[ABS]	1.0788	1.5023	
FLOODING Intermediate: (log10(ABS)+2)/2	[INT]	0.6777	0.7256	
FLOODING Ordinate	[ORD]	0.03014	0.02058	
Cf, for Pall Rings	{Cf}	20	20	
g'c - Stipulate gcs, gcm, or gch	{gcm}	1.158E+05	1.158E+05	
Water Viscosity, cP	{WV1}	1.12171	1.12171	
Air Viscosity, cP	{AV1}	0.01736	0.01736	
J (Use only with Treybal, 3rd Ed.)	{J}	1.502	1.502	
K (Treybal, 3rd Ed. Ordinate Constant)		5.520E-05	5.520E-05	
Air Loading Rate AT FLOODING				
(lb/min)/ft <sup>2</sup>	[ALR]	23.37	19.31	
Flooding Factor				
Adjusted ORD, FF*ORD [Hylton] ##	{FF}	0.4	0.4	
Derived Air Loading Rate	[AORD]	0.01205	0.00823	
(lb/min)/ft <sup>2</sup>	[DALR]	9.35	7.72	
Derived ORD, Bolles & Fair	[DORD]	0.004822	0.003294	
...Also [DORDB] for Benzene, & [DORDT] for Trichloroethylene				
Cross Section AREA, ft <sup>2</sup> , APM/DALR				
STRIPPER DIAMETER, ft	[AREA]	14.46057	12.56523	
Stripper Diameter, inches	[DIA]	4.291	4.000	
	[din]	51.491	47.998	

[TAB5]  
VOC-2.100

TABLE A-5  
VAPOR HTU CALCULATIONS FOR PACKED STRIPPER

Vapor Packing Parameter, VPP  
For 5/8 in Pall Rings 70 70.7857 70.7857  
For 1 in Pall Rings 48 73.2619 73.2619  
For 1 1/2 in Pall Rings\*\* 28 106.0357 106.0357  
For 2 in Pall Rings 20 138.8095 138.8095  
\*\* Interpolated value [VPP] 138.8095 138.8095

-----  
Taken From Earlier Entries & Calculations

Air Viscosity, lb/ft sec {AV2} 1.167E-05  
Air Density, lb/ft<sup>3</sup> {AD} 0.07631  
Air Pressure, Atmospheres {PAT} 1.00  
Temperature, Kelvins {TK} 288.71  
Molecular Weight of Air {MWA} 28.96  
Molecular Weight of Key Comp. 78.11 28.96  
1/MWA 0.034530 131.39  
1/MWK 0.012802 0.034530  
[1/MWA + 1/MWK]<sup>0.5</sup> 0.007611 0.007611  
[RCP] 0.217561 0.205284

Stripper Diameter, ft \*\*\* {DIA} 4.291 4.000

-----  
Collision Function Calculations  
(Ref. Fig. 2.5 Treybal)

Abcissa  
(Log10(ABS2)+1)/3.60206  
Collision Function, Vapor [Ordinate] {ABS2} 1.6037 1.5594  
[INT2] 0.33457 0.33119  
[CFV] 0.59265 0.59927

Molecular Separations  
Air-Key Contaminant {MSEP} 0.4530 0.4658

Diffusivity, m<sup>2</sup>/sec {DAK} 8.9190E-06 7.8949E-06  
Diffusivity, ft<sup>2</sup>/sec {DAKA} 9.5954E-05 8.4937E-05

Schmidt Number, Vapor [SV] 1.59348 1.80018

HTU, AIR, ft [HA] 1.1861 1.1588

\*\*\* This diameter value is used for calculation of the required volume of packing, and for the cross sectional area of the packed column stripper. BUT ... an artificial diameter of 2 feet appears in the calculation of the HTU [HA] in this table. [Hylton, ORNL]

[TAB6]  
VOC-2.100

TABLE A-6  
LIQUID HTU CALCULATIONS FOR PACKED STRIPPER

Water Loading Rate, lb/ft <sup>2</sup> hour	[WLR]	17294.120	19902.772
Intermediate: (Log10(ABS)-2.30103)/2.30103	[INT3]	0.84174	0.86826
Liquid Packing Parameter, LPP			
For 5/8 in Pall Rings	[LPP1]	0.1192	0.1319
For 1 in Pall Rings	[LPP2]	0.1002	0.1102
For 1 1/2 in Pall Rings**	[LPP3]	0.1193	0.1280
For 2 in Pall Rings	[LPP4]	0.1384	0.1459
** Interpolated value	[LPP]	0.1384	0.1459
Intermediate: (FF-0.5)/0.32	[INT4]	-0.3125	-0.3125
Flood Point Coefficient	[FPC]	1.000	1.000
Height of Packed Bed, ft	{HPB}	10	10
Water Viscosity, Centipoise	{WV1}	1.12171	1.12171
Water Viscosity, Pa sec	[WVSI]	1.122E-03	1.122E-03
Water Viscosity, lb/ft sec	{WV2}	7.538E-04	7.538E-04
Water Density, lb/ft <sup>3</sup>	{WD}	62.358	62.358
Water Diffusivity, m <sup>2</sup> /sec	[WAK]	8.0097E-10	8.0097E-10
Water Diffusivity, ft <sup>2</sup> /sec	[WAKA]	8.6171E-09	8.6171E-09
Schmidt Number - Water	[SW]	1402.73	1402.73
HTU, WATER, ft	[HW]	5.1830	5.4647

[TAB7]  
VOC-2.100                      OVERALL HEIGHT OF TRANSFER UNIT FOR PACKED STRIPPER

Ref. Treybal p. 311, eq. 8.56

Overall Height = (HTU, WATER, ft) + (HTU, AIR, ft)/S

Recall from previous calculations

HTU, AIR, ft	{HA}	1.1861	1.1588
HTU, WATER, ft	{HW}	5.1830	5.4647
HTU, TOTAL, ft	{HT}	5.4795	5.7544



[TAB8] VOC-2.100      NUMBER OF TRANSFER UNITS CALCULATIONS FOR PACKED STRIPPER

Ref. Treybal p. 309, eqn. 8.51

IN WATER

Contaminant Concentration, ppb IN	{PPBI}	100	100
Contaminant Mole Fraction, IN	{CMFI}	2.306E-08	1.371E-08
Contaminant Concentration, ppb OUT	{PPBO}	1	1
Contaminant Mole Fraction, OUT	{CMFO}	2.306E-10	1.371E-10
Contaminant Concentration Change, ppb	{PPBD}	99	99
Contaminant Removal Rate, Pounds/Min	{RRPPM}	4.126E-04	4.126E-04
Contaminant Removal Rate, Pound Mols/Min	{RRPMM}	5.283E-06	3.141E-06
Number of Transfer Units Required	{NTU}	5.761	5.761

TOTAL HEIGHT OF COLUMN

Total = Total HTU \* NTU

Total Height Required, ft

Safety Factor

TOTAL HEIGHT OF PACKING, FT

[HTR]	31.57	33.15
{SF}	1.7	1.7
[HTOT]	53.67	56.36

[TAB9]  
VOC-2.100

TABLE A-9 [DATA LOOKUP TABLE]  
CALCULATION OF PACKED STRIPPER PRESSURE GRADIENT  
[See associated documentation for discussion of method]

Previously calculated Treybal Abscissa and Ordinate values for Benzene and TCE

ABSCISSA	[ABSB] [ABST]	1.0788	1.5023	ORDINATE			0.0048	0.0033		
Row Number [RN]	Treybal Abscissa [TA]	[SELB] [SELB]	Column Number--> [SELT] [TORD] [SELODB] [SELODT]	1 0.00005 0 0	2 0.00010 0 0	3 0.00050 0 0	4 0.00100 0 0	5 0.002 0 5	6 0.004 6 0	
1	0.015	0	0	0.060	0.130	0.900	2.00	2	8	
2	0.020	0	0	0.062	0.133	0.980	2.23	5	10	
3	0.040	0	0	0.064	0.136	1.064	2.47	8	16	
4	0.060	0	0	0.066	0.142	1.147	2.72	10	18	
5	0.100	0	0	0.069	0.148	1.234	2.98	16	22	
6	0.150	0	0	0.072	0.156	1.325	3.29	18	24	
7	0.200	0	0	0.075	0.166	1.426	3.75	20	26	
8	0.300	0	0	0.081	0.182	1.542	4.33	22	30	
9	0.400	0	0	0.089	0.204	1.687	5.10	25	35	
10	0.500	0	0	0.101	0.238	1.877	6.16	28	40	
11	0.600	0	0	0.120	0.288	2.140	7.60	30	45	
12	0.800	0	0	0.149	0.360	2.513	9.55	33	52	
13	1.000	13	0	0.193	0.457	3.033	12.09	35	60	
14	1.500	0	14	0.240	0.580	3.700	15.25	40	85	
15	2.000	0	0	0.293	0.720	4.367	18.80	48	105	
16	3.000	0	0	0.347	0.860	5.033	22.40	75	200	
17	4.000	0	0	0.400	1.000	5.700	26.00	125	500	

\*\*\* PRESSURE GRADIENTS, FROM LOOKUP TABLE [PGT]

	BENZENE	TCE
*** In Pa/meter----->	60.00	40.00
*** In lb/in^2 ft----->	0.0027	0.0018
*** In inches H2O/ft-->	0.0734	0.0490

[TAB9]  
VOC-2.100

TABLE A-9 [DATA LOOKUP TABLE] (CONCLUDED)  
CALCULATION OF PACKED STRIPPER PRESSURE GRADIENT  
[See associated documentation for discussion of method]

Previously calculated Treybal Abscissa and Ordinate values for Benzene and TCE

ABSCISSA		[ABSB] [ABST]	1.0788	1.5023	ORDINATE		[DORDB] [DORDT]	0.0048 0.0033					
Row Number [RN]	Treybal Abscissa [TA]	[SELB] [SELT]	Column Number--> [CN] [TORD] [SELODB] [SELODT]	[PCT]----->	7	8	9	10	11	12	13	14	
1	0.015	0	0	0	0	0	0	0	0	0	0	0	
2	0.020	0	0	0	15	20	35	80	150	230	350	490	
3	0.040	0	0	0	18	25	40	82	155	240	360	500	
4	0.060	0	0	0	22	30	45	85	175	275	400	580	
5	0.100	0	0	0	25	35	48	90	185	300	440	600	
6	0.150	0	0	0	30	40	52	95	205	380	580	750	
7	0.200	0	0	0	35	45	60	100	250	400	680	900	
8	0.300	0	0	0	40	50	65	125	300	500	800	1200	
9	0.400	0	0	0	45	60	75	150	400	700	1200		
10	0.500	0	0	0	50	70	80	180	550	1100			
11	0.600	0	0	0	60	85	95	280	900				
12	0.800	0	0	0	70	90	115	320	1200				
13	1.000	13	0	0	80	100	150	490					
14	1.500	0	14	0	90	125	160	600					
15	2.000	0	0	0	140	200	300						
16	3.000	0	0	0	200	380	600						
17	4.000	0	0	0	500	1100							

[TAB10] VOC-2.100 SUMMARY OF PACKED COLUMN STRIPPER GEOMETRY CALCULATIONS

OPERATING VARIABLES

Operating Temperature, F	{TF}	60.00
Inlet Gas Pressure, Atm	{PAT}	1.00
Water Feed Rate, Gallons/Minute	{WGM}	500
Contaminant Concentration, ppb IN	{PPBI}	100
Contaminant Concentration, ppb OUT	{PPBO}	1
Stripping Factor	{S}	4
Packing Type - Metal Pall Rings		
Packing Size	{SIZE}	50(2)
Packing Factor	{CF}	20
Correlation Factor, J	{J}	1.502
Flooding Factor	{FF}	0.40
Height of Packed Bed	{HPB}	10
Height Safety Factor	{SF}	1.7

DESIGN OUTPUTS

=====		TCE*
Benzene		
Stripper Diameter, ft	{DIA}-->	4.291 4.000
HTU AIR, ft	{HA}	1.1861 1.1588
HTU WATER, ft	{HW}	5.1830 5.4647
HTU TOTAL, ft	{HT}-->	5.4795 5.7544
Number of Transfer Units Required	{NTU}	5.761 5.761
Total Height Required, ft	{HTR}-->	31.568 33.152
Safety Adjusted Height Required, ft	{HTOT}-->	53.665 56.358
VOLUME OF PACKING, $HTOT * (\pi/4) * DIA^2$ , ft <sup>3</sup>	{PVOL}-->	776.031 708.153
PRESSURE GRADIENT, lb/in <sup>2</sup> ft	{PAGB, PAGT}----->	0.0026531 0.0017688

NOTE: --> in rows just above highlights the key geometrical data.

[TAB11]  
TABLE A-11  
AIR BLOWER & WATER PUMP CALCULATIONS FOR PACKED STRIPPER  
VOC-2.100

## INPUTS

Vertical Lift of Water			
Groundwater Depth, ft	{HGW}	30	30
Total Stripper Height, ft	{HTOT}	53.665	56.358
Total Vertical Lift, ft			
= HGW + HTOT + 10	[Z]	93.665	96.358
Friction Loss Factors			
Fanning Friction Factor	{F}	0.008	0.008
Horizontal Pile Length, ft	{HPL}	100	100
Total Pipe Length = Z + HPL, ft	{TPL}	193.665	196.358
Pipe Internal Diameter, inches	{PDIN}	7	7
Pipe Internal Diameter, ft	[PD]	0.5833	0.5833
Consolidated Friction Loss Coefficient, for Valves, Elbows, etc.	{Kf}	15	15
TOTAL FRICTION LOSS FACTOR	{HF}	25.62	25.77

## AIR BLOWER CALCULATIONS

SLOPE SLOWER CALCULATIONS			
Pressure Gradient, lb/in <sup>2</sup> ft,	{ACFM}	1771.07	1271.89
Pressure Gradient, lb/ft <sup>2</sup> ft	{PAGB, PAGT}	0.0026531	0.0017688
TOTAL PRESSURE DROP, lb/in <sup>2</sup>	[PB, PT]	0.3821	0.2547
Total Pressure Drop, inches of water	[PPD]	0.1424	0.0997
	[INPD]	3.94	2.76

**Air Density, lb/ft<sup>3</sup>**

**Packing Height, TOTAL, ft**

**PUMP POWER:** Horsepower, electric  
Watts  
Kilowatts, [KW1B], [KW2B]

## WATER LIFT PUMP CALCULATIONS

**PUMP POWER:** Horsepower, electric  
Watts  
Kilowatts, [KW2B], [KW2C]

TOTAL STRIPPER POWER, kW, [KWSB], [KWST]

[TAB12] TABLE A-12  
VOC-2.100 CARBON USE CALCULATIONS FOR OFF GAS TREATMENT

AIR STREAM CALCULATIONS

Contaminant Removal Rate, Pounds/Min	{RRPPM}	4.126E-04	4.126E-04
Air Stream Rate, Pounds/Min	{APM}	135.15	97.06
AIR STREAM CONCENTRATION, ppm by WEIGHT	[WRAT]	3.05	4.25
Contaminant Removal Rate, Pound Mols/Min	{RRPMM}	5.283E-06	3.141E-06
Air Stream Rate, Pound Mols/Min	{APMM}	4.67	3.35
AIR STREAM CONCENTRATION, ppm by MOLS	[MRAT]	1.13	0.94

DATA

FOR {WGM} 500

Breakthrough Capacity [Freundlich] \*  
lb contaminant/lb carbon

[BC] 0.00520 0.03809

WATER PROCESSING, INFORMATION, PER DAY

Total Pounds Water Processed	[TPW]	6.002E+06	6.002E+06
Total Pounds Contaminant Stripped	[TCS]	0.594	0.594
POUNDS OF CARBON REQUIRED/DAY	[CARR]	114.16	15.60
Carbon Use Safety Factor	{CSF}	1.5	1.5
ADJUSTED CARBON POUNDS PER DAY	[CPD]	171.25	23.40
Carbon Bulk Density, lb/ft <sup>3</sup> **	{CD}	30	30
ADJUSTED CARBON, CUBIC FEET PER DAY	[CFPD]	5.708	0.780

\* Compare with Eglin AFB breakthrough graphs provided by Lucero and Hylton, at 2 ppm benzene.

\*\* Bulk densities vary SUBSTANTIALLY depending upon the source raw material and the method of preparation. The value shown is an approximate mean value of those reported in the Chemical Engineers Handbook.

TABLE A-D1B  
PACKED COLUMN STRIPPER  
SINGLE VARIABLE DESIGN OUTPUT INFORMATION

BENZENE

VARIABLE INPUT	Treybal, 3rd Ed.	STRIPPER DIAMETER	NUMBER TRANSFER UNITS	HEIGHT VAPOR TRANSFER UNIT	HEIGHT LIQUID TRANSFER UNIT	STRIPPER HEIGHT	STRIPPER WEIGHT	PACKING VOLUME	PRESSURE GRADIENT	TOTAL PRESSURE DROP, AIR
CRI	ABSCISSA ORDINATE	feet	{NTU1}	feet {HAL}	feet {HW1}	{HTOT1}	{SWP1}	feet {PVOL1}	in H <sub>2</sub> O/ft {PAGBI}	inches H <sub>2</sub> O {INPDI}
5.000	1.0788	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
10.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
15.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
20.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
25.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
30.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
35.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
40.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
45.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
50.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
55.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
60.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
65.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
70.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
75.000	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94

[1] Adjusted for HEIGHT DESIGN SAFETY FACTOR, {SF} = 1.7

[2] Based upon adjusted height, and 0.25 inch steel construction.

[3] Based upon the adjusted stripper height.

[4] Based upon the adjusted stripper height.

[5] WGM may also appear as the variable input for some sensitivity analysis runs.

TABLE A-D1B  
PACKED COLUMN STRIPPER  
SINGLE VARIABLE DESIGN OUTPUT INFORMATION (CONCLUDED)

VARIABLE INPUT	BENZENE				
	AIR FLOW RATE ft <sup>3</sup> /min {ACFMB}	WATER FLOW RATE {5} gal/min {WGM}	AIR ***** {KW1B}	WATER ***** {KW2B}	TOTAL ***** {KWSB}
CRI					
5.000	1771.07	500.00	1.37	13.57	14.94
10.000	1771.07	500.00	1.37	13.57	14.94
15.000	1771.07	500.00	1.37	13.57	14.94
20.000	1771.07	500.00	1.37	13.57	14.94
25.000	1771.07	500.00	1.37	13.57	14.94
30.000	1771.07	500.00	1.37	13.57	14.94
35.000	1771.07	500.00	1.37	13.57	14.94
40.000	1771.07	500.00	1.37	13.57	14.94
45.000	1771.07	500.00	1.37	13.57	14.94
50.000	1771.07	500.00	1.37	13.57	14.94
55.000	1771.07	500.00	1.37	13.57	14.94
60.000	1771.07	500.00	1.37	13.57	14.94
65.000	1771.07	500.00	1.37	13.57	14.94
70.000	1771.07	500.00	1.37	13.57	14.94
75.000	1771.07	500.00	1.37	13.57	14.94



[D2B]  
VOC-2.100

TABLE A-D2B  
CARBON ADSORPTION AND CATALYTIC INCINERATION  
SINGLE VARIABLE DESIGN OUTPUT INFORMATION

BENZENE

CATALYSIS UNIT SIZE INFORMATION												
VARIABLE INPUT	AIR FLOW RATE	BENZENE MOLAR CONCENTRATION	CARBON DAILY USE	CARBON CYCLE USE	CARBON DESIGN SIZE	CARBON UNITS PURCHASED	CARBON CAPITAL PURCHASE	CARBON RECYCLED ANNUALLY	AIR FAN POWER	AIR HEATER	AIR FLOW	AIR HEATER
CRI	lb/min {APM1}	ppm {MBAT1}	lb/day {CPD1}	lb/cycle {CCU}	lb/cycle {CDS}	{3} {CUP}	pounds {4}	pounds {5}	kilowatts {6} {KWCB}	MMBTU/yr {8} {FUEL1B}	ft <sup>3</sup> /min {7} {ACAT}	MMBTU/yr {8} {FUEL2B}
5,000	135.2	1.1	171	856	856	2	1712	53129	6.84	935	2657	26188
10,000	135.2	1.1	171	1712	1712	2	3425	53129	6.84	935	2657	26188
15,000	135.2	1.1	171	2569	2569	2	5137	53129	6.84	935	2657	26188
20,000	135.2	1.1	171	3425	3425	2	6850	53129	6.84	935	2657	26188
25,000	135.2	1.1	171	4281	4281	2	8562	53129	6.84	935	2657	26188
30,000	135.2	1.1	171	5137	5137	2	10275	53129	6.84	935	2657	26188
35,000	135.2	1.1	171	5994	5994	2	11987	53129	6.84	935	2657	26188
40,000	135.2	1.1	171	6850	6850	2	13700	53129	6.84	935	2657	26188
45,000	135.2	1.1	171	7706	7706	2	15412	53129	6.84	935	2657	26188
50,000	135.2	1.1	171	8562	8562	2	17125	53129	6.84	935	2657	26188
55,000	135.2	1.1	171	9419	9419	2	18837	53129	6.84	935	2657	26188
60,000	135.2	1.1	171	10275	10275	2	20550	53129	6.84	935	2657	26188
65,000	135.2	1.1	171	11131	11131	2	22262	53129	6.84	935	2657	26188
70,000	135.2	1.1	171	11987	11987	2	23974	53129	6.84	935	2657	26188
75,000	135.2	1.1	171	12843	12843	2	25687	53129	6.84	935	2657	26188

BASED UPON CATALYTIC UNIT SIZE

[7] Based upon CATALYTIC UNIT SIZE

[7] Based upon CATALYTIC UNIT SIZE

[1] Corrected for CARBON UNIT SIZE SAFETY FACTOR (CSF) = 1.50

[2] Adjusted for CARBON RECYCLE INTERVAL, days (CRI) = 75

[3] One spare adsorption unit purchased, for contingency and for shift of throughput during carbon regeneration.

[4] Subsequent to initial purchase of carbon, the regeneration cycle provides for adequate make up with new carbon.

[5] Based upon Load Factor (LF) = 0.85 and stipulated values of CSF and CRI.

[6] Sized at 5X the air fan requirements of stripper.

[8] Air stream heating for both carbon adsorption and catalysis units.

MMBTU = Millions BTU

(D3B)  
VOC-2.100

TABLE A-D3B  
PACKED COLUMN STRIPPER

BENZENE

CAPITAL EXPENDITURES										ANNUAL EXPENSE				* *	
VARIABLE INPUT	AIR FAN & MOTOR (1)	WATER PUMP & MOTOR (1)	STRIPPER SHELL (1)	PLASTIC PALL RINGS (1)	TOTAL EQUIPMENT DELIVERED (6)	TOTAL EQUIPMENT INSTALLED (2)	MAINTENANCE OF PALL RING PACKING (3)	LABOR ONE FTE	ELECTRICAL POWER COSTS	MISC & OEM (4)	UNLOADED TOTAL ANNUAL EXPENSE		LOADED TOTAL ANNUAL EXPENSE		
											1990 \$	1990 \$	1990 \$	1990 \$	1990 \$
CRI	1977 \$	1977 \$	1977 \$	1990 \$	1990 \$	1990 \$	1990 \$	1990 \$	1990 \$	1990 \$	1990 \$	1990 \$	1990 \$	1990 \$	
5.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
10.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
15.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
20.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
25.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
30.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
35.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
40.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
45.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
50.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
55.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
60.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
65.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
70.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	
75.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149	115149	115149	

- [1] Materials of construction costs adjusted upward via MATERIALS MULTIPLIER FACTOR [MMF] = 1.70
- [2] Adjusted upward via EQUIPMENT INSTALLATION FACTOR [EIFS] = 2.20
- [3] Pall ring maintenance at 25% of 1990 purchase cost.
- [4] Factor x Installed Capital Equipment Costs [OH] = 0.15
- [5] Overhead Rate on Total Annual Expense, % [OHR] = 100
- [6] Average Annual Inflation: 1977-90 [I] = 0.0484

TABLE A-D4B  
CARBON ADSORPTION UNITS  
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

BENZENE										
CAPITAL EXPENDITURES					ANNUAL EXPENSE					
VARIABLE INPUT	NEW CHARCOAL PURCHASED (1)	NEW CHARCOAL PURCHASED	CARBON SORPTION UNITS (2)	CARBON SORPTION UNITS	TOTAL EQUIPMENT INSTALLED (3)	ANNUAL FUEL OIL COSTS (5)	CHARCOAL RECYCLE COSTS	ELECTRICAL POWER COSTS	UNLOADED TOTAL ANNUAL EXPENSE	LOADED TOTAL ANNUAL EXPENSE (4)
	1977\$	1990\$	1982 \$	1990 \$	1990 \$ [CAPCB]	1990 \$	1990 \$	1990 \$	1990 \$	1990 \$ [EXPCB]
5.000	1712	3166	78485	114553	188349	5752	44368	3055	53175	66469
10.000	3425	6331	84171	122851	206691	5752	44368	3055	53175	66469
15.000	5137	9497	89856	131149	225033	5752	44368	3055	53175	66469
20.000	6850	12663	95541	139447	243375	5752	44368	3055	53175	66469
25.000	8562	15829	101227	147745	261717	5752	44368	3055	53175	66469
30.000	10275	18994	106912	156043	280059	5752	44368	3055	53175	66469
35.000	11987	22160	112598	164341	298401	5752	44368	3055	53175	66469
40.000	13700	25326	118283	172639	316743	5752	44368	3055	53175	66469
45.000	15412	28491	123968	180937	335085	5752	44368	3055	53175	66469
50.000	17125	31657	129654	189235	353427	5752	44368	3055	53175	66469
55.000	18837	34823	135339	197533	371769	5752	44368	3055	53175	66469
60.000	20550	37989	141024	205831	390111	5752	44368	3055	53175	66469
65.000	22262	41154	146710	214129	408453	5752	44368	3055	53175	66469
70.000	23974	44320	152395	222427	426795	5752	44368	3055	53175	66469
75.000	25687	47486	158081	230725	445137	5752	44368	3055	53175	66469

[1] Based upon \$1.00/lb, 1977 Prices.

[2] There is a shift in the cost correlation function at a size of about 10,000 lb carbon.

[3] Using Equipment Installation Factor [EIF] as shown in Table 1.

[4] Overhead at 25% of total annual expense. The primary burden of the overhead is loaded on the packed column stripper.

[5] For heating of air stream to lower relative humidity before input to carbon adsorption units.

(DSB)  
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TABLE A-DSB  
CATALYTIC INCINERATION UNIT  
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

BENZENE																	
CAPITAL EXPENDITURES				ANNUAL EXPENSE													
				* *	* *												
VARIABLE INPUT	UNIT COST	UNIT COST	TOTAL EQUIPMENT INSTALLED (1)	1990 \$ [CAPCATB]	ANNUAL FUEL OIL COSTS	1990 \$	ELECTRICAL POWER COSTS	1990 \$	ANNUAL CATALYST COST	1979 \$	ANNUAL CATALYST COST	1990 \$	TOTAL	1990 \$ [EXPCATB]	LOADED TOTAL ANNUAL EXPENSE (2)		
CRI		1979 \$	1990 \$														
5.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
10.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
15.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
20.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
25.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
30.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
35.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
40.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
45.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
50.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
55.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
60.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
65.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
70.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			
75.000	29081		48911	78257	161058	3055				2678		4505	168618	210772			

[1] Using Equipment Installation Factor [EIF] as shown in Table 1.

[2] Overhead at 25% of total annual expense. The primary burden of the overhead is placed on the packed column stripper.

TABLE A-D6B  
COMBINED EQUIPMENT SYSTEMS  
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

VARIABLE INPUT	BENZENE											
	PACKED STRIPPER			CARBON SORPTION			PACKED STRIPPER & CARBON SORPTION			CATALYSIS UNIT		
										PACKED STRIPPER & CATALYSIS UNIT		
	TOTAL FIXED CAPITAL	TOTAL ANNUAL EXPENSE	1990 \$ (CAPSB)	TOTAL FIXED CAPITAL	TOTAL ANNUAL EXPENSE	1990 \$ (CAPCB)	TOTAL FIXED CAPITAL	COMBINED FIXED CAPITAL	COMBINED EXPENSE	TOTAL FIXED CAPITAL (CAPCATB)	TOTAL ANNUAL EXPENSE (EXPCATB)	COMBINED FIXED CAPITAL EXPENSE
CRI												
5.000	172226	115149		188349	66469		360575	181618	181618	78257	210772	250483
10.000	172226	115149		206691	66469		378917	181618	181618	78257	210772	250483
15.000	172226	115149		225033	66469		397259	181618	181618	78257	210772	250483
20.000	172226	115149		243375	66469		415601	181618	181618	78257	210772	250483
25.000	172226	115149		261717	66469		433943	181618	181618	78257	210772	250483
30.000	172226	115149		280059	66469		452285	181618	181618	78257	210772	250483
35.000	172226	115149		298401	66469		470627	181618	181618	78257	210772	250483
40.000	172226	115149		316743	66469		488969	181618	181618	78257	210772	250483
45.000	172226	115149		335085	66469		507311	181618	181618	78257	210772	250483
50.000	172226	115149		353427	66469		525653	181618	181618	78257	210772	250483
55.000	172226	115149		371769	66469		543995	181618	181618	78257	210772	250483
60.000	172226	115149		390111	66469		562337	181618	181618	78257	210772	250483
65.000	172226	115149		408453	66469		580679	181618	181618	78257	210772	250483
70.000	172226	115149		426795	66469		599021	181618	181618	78257	210772	250483
75.000	172226	115149		445137	66469		617363	181618	181618	78257	210772	250483

Compare with Table D7B, which is for the rotary stripper. In D7B, the two columns for the packed stripper are replaced by calculation of the fixed capital and the annual [non-capital] expense for the rotary stripper.

The capital and expense figures for the carbon adsorption and the catalytic incineration are identical in D6B and D7B, however.

TABLE A-D7B  
COMBINED EQUIPMENT SYSTEMS  
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

BENZENE

VARIABLE INPUT	ROTARY STRIPPER  (1) 1990 \$	FANS, PUMPS, MOTORS (2) 1990 \$	ROTARY STRIPPER			CARBON SORPTION			ROTARY STRIPPER & CARBON SORPTION			CATALYSIS UNIT			ROTARY STRIPPER & CATALYSIS UNIT		
			TOTAL FIXED CAPITAL (3) {CAPRB}	TOTAL ANNUAL EXPENSE (4) {EXPRB}	TOTAL FIXED CAPITAL (5) {CAPCB}	TOTAL ANNUAL EXPENSE (5) {EXPCB}	COMBINED FIXED CAPITAL (5) {CAPCB}	COMBINED EXPENSE (5) {EXPCB}	TOTAL FIXED CAPITAL (5) {CAPCATB}	TOTAL ANNUAL EXPENSE (5) {EXPCATB}	COMBINED FIXED CAPITAL (5) {CAPCB}	COMBINED EXPENSE (5) {EXPCB}	TOTAL FIXED CAPITAL (5) {CAPCATB}	TOTAL ANNUAL EXPENSE (5) {EXPCATB}	COMBINED FIXED CAPITAL (5) {CAPCB}	COMBINED EXPENSE (5) {EXPCB}	
CRI																	
5.000	153043	17027	272112	128496	188349	66469	460462	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
10.000	153043	17027	272112	128496	206691	66469	478804	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
15.000	153043	17027	272112	128496	225033	66469	497146	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
20.000	153043	17027	272112	128496	243375	66469	515488	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
25.000	153043	17027	272112	128496	261717	66469	533830	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
30.000	153043	17027	272112	128496	280059	66469	552172	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
35.000	153043	17027	272112	128496	298401	66469	570514	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
40.000	153043	17027	272112	128496	316743	66469	588856	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
45.000	153043	17027	272112	128496	335085	66469	607198	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
50.000	153043	17027	272112	128496	353427	66469	625540	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
55.000	153043	17027	272112	128496	371769	66469	643882	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
60.000	153043	17027	272112	128496	390111	66469	662224	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
65.000	153043	17027	272112	128496	408453	66469	680566	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
70.000	153043	17027	272112	128496	426795	66469	698908	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	
75.000	153043	17027	272112	128496	445137	66469	717250	194965	78257	210772	350369	1990 \$	78257	210772	350369	1990 \$	

[1] Based upon a Cost/Capacity scaling factor = 0.304

The purchased equipment cost includes one full charge of packing materials.  
It also provides for stainless steel construction materials.

[2] Uses the values previously calculated for the packed stripper water pump and air fans.  
Then double to allow for additional power to drive the rotors of the rotary stripper.

[3] Sum of two preceding columns. Equipment installation factor [EIFC] = 1.60  
which is the same factor used for the carbon adsorption and the catalytic incineration units.

[4] Uses values from the packed stripper, except for the addition of extra electrical power to handle the rotational units. See [2] above.

[5] Identical to values already calculated for the carbon adsorption and for the catalytic incineration units, at corresponding operating conditions.

NOTE: Data for rotary stripper are calculated in this table. Data for carbon adsorption and catalytic incineration units are copied from earlier tables.

TABLE A-D1T  
PACKED COLUMN STRIPPER  
SINGLE VARIABLE DESIGN OUTPUT INFORMATION

TCE													
VARIABLE INPUT	Treybal, 3rd Ed.	ABSCISSA	ORDINATE	STRIPPER DIAMETER	NUMBER TRANSFER UNITS	HEIGHT VAPOR TRANSFER UNIT	HEIGHT LIQUID TRANSFER UNIT	STRIPPER HEIGHT	STRIPPER WEIGHT	PACKING VOLUME	PRESSURE GRADIENT	PRESSURE DROP, AIR	TOTAL
CRI	{ABST}	{DORDT}		feet {DIA2}	{NTU2}	feet {HA2}	feet {HW2}	{HTOT2}	{SWP2}	{PVOL2}	in H <sub>2</sub> O/ft {PAGTI}	inches H <sub>2</sub> O {INPD2}	
5.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
10.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
15.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
20.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
25.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
30.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
35.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
40.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
45.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
50.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
55.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
60.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
65.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
70.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	
75.000	1.5023	0.003294		4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76	

[1] Adjusted for HEIGHT DESIGN SAFETY FACTOR, [SF] = 1.7

[2] Based upon adjusted height, and 0.25 inch steel construction.

[3] Based upon the adjusted stripper height.

[4] Based upon the adjusted stripper height.

[5] WGM may also appear as the variable input for some sensitivity analysis runs.

TABLE D1T (CONCLUDED)  
 PACKED COLUMN STRIPPER  
 SINGLE VARIABLE DESIGN OUTPUT INFORMATION

TCE

VARIABLE INPUT	AIR FLOW RATE ft <sup>3</sup> /min {ACFM2} [ACFMT]	WATER FLOW RATE {S} gal/min {WGM}	STRIPPER POWER DEMAND			
CRI			AIR ***** {KW1T}	WATER kilowatts {KW2T}	TOTAL ***** {KWST}	
5.000	1271.89	500.00	0.41	13.94	14.35	
10.000	1271.89	500.00	0.41	13.94	14.35	
15.000	1271.89	500.00	0.41	13.94	14.35	
20.000	1271.89	500.00	0.41	13.94	14.35	
25.000	1271.89	500.00	0.41	13.94	14.35	
30.000	1271.89	500.00	0.41	13.94	14.35	
35.000	1271.89	500.00	0.41	13.94	14.35	
40.000	1271.89	500.00	0.41	13.94	14.35	
45.000	1271.89	500.00	0.41	13.94	14.35	
50.000	1271.89	500.00	0.41	13.94	14.35	
55.000	1271.89	500.00	0.41	13.94	14.35	
60.000	1271.89	500.00	0.41	13.94	14.35	
65.000	1271.89	500.00	0.41	13.94	14.35	
70.000	1271.89	500.00	0.41	13.94	14.35	
75.000	1271.89	500.00	0.41	13.94	14.35	



(D2T)  
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TABLE A-D2T  
CARBON ADSORPTION AND CATALYTIC INCINERATION  
SINGLE VARIABLE DESIGN OUTPUT INFORMATION

TCE

VARIABLE INPUT	AIR FLOW RATE {APM2} lb/min	BENZENE MOLAR CONCENTRATION ppm {MRAT2}	CARBON DAILY USE lb/day {CPD2}	CARBON CYCLE USE lb/cycle {CCUT}	CARBON DESIGN SIZE {1,2} pounds {CDST}	CARBON UNITS PURCHASED {3} {CUPT}	CARBON CAPITAL PURCHASE {4} pounds	CARBON RECYCLED ANNUALLY {5} pounds {CRAT}	AIR FLOW RATE {6} kilowatts {KWCT}	AIR HEATER ABTU/yr {FUEL1T}	CATALYTIC UNIT SIZE INFORMATION	
											AIR FLOW ft <sup>3</sup> /min {ACATT}	AIR HEATER MMBTU/yr {FUEL2T}
CRI												
5.000	97.1	0.9	23	117	117	2	234	7260	2.06	672	1908	18807
10.000	97.1	0.9	23	234	234	2	468	7260	2.06	672	1908	18807
15.000	97.1	0.9	23	351	351	2	702	7260	2.06	672	1908	18807
20.000	97.1	0.9	23	468	468	2	936	7260	2.06	672	1908	18807
25.000	97.1	0.9	23	585	585	2	1170	7260	2.06	672	1908	18807
30.000	97.1	0.9	23	702	702	2	1404	7260	2.06	672	1908	18807
35.000	97.1	0.9	23	819	819	2	1638	7260	2.06	672	1908	18807
40.000	97.1	0.9	23	936	936	2	1872	7260	2.06	672	1908	18807
45.000	97.1	0.9	23	1053	1053	2	2106	7260	2.06	672	1908	18807
50.000	97.1	0.9	23	1170	1170	2	2340	7260	2.06	672	1908	18807
55.000	97.1	0.9	23	1287	1287	2	2574	7260	2.06	672	1908	18807
60.000	97.1	0.9	23	1404	1404	2	2808	7260	2.06	672	1908	18807
65.000	97.1	0.9	23	1521	1521	2	3042	7260	2.06	672	1908	18807
70.000	97.1	0.9	23	1638	1638	2	3276	7260	2.06	672	1908	18807
75.000	97.1	0.9	23	1755	1755	2	3510	7260	2.06	672	1908	18807

[1] Corrected for CARBON UNIT SIZE SAFETY FACTOR {CSF} = 1.50

[2] Adjusted for CARBON RECYCLE INTERVAL, days {CRI} = 75

[3] One spare adsorption unit purchased, for contingency and for shift of throughput during carbon regeneration.

[4] Subsequent to initial purchase of carbon, the regeneration cycle provides for adequate make up with new carbon.

[5] Based upon Load Factor {LF} = 0.85 and stipulated values of CSF and CRI.

[6] Sized at 5X the air fan requirements of stripper.

[7] Based upon CATALYTIC UNIT SIZE SAFETY FACTOR {CSF} = 1.5

[8] Air stream heating for both carbon adsorption and catalysis units.

MMBTU = Millions BTU

TABLE A-D3T  
PACKED COLUMN STRIPPER

CAPITAL EXPENDITURES													ANNUAL EXPENSE				TCE																					
* *													* *				* *																					
VARIABLE INPUT													MAINTENANCE OF PALL RING PACKING [3]				LABOR ONE FTE		ELECTRICAL POWER COSTS		MISC & O&M [4]		UNLOADED TOTAL ANNUAL EXPENSE		LOADED TOTAL ANNUAL EXPENSE													
AIR FAN & MOTOR [1]													WATER PUMP & MOTOR [1]				STRIPPER SHELL [1]		PLASTIC PALL RINGS [1]		TOTAL EQUIPMENT DELIVERED [6]		TOTAL EQUIPMENT INSTALLED [2]		1990 \$		1990 \$											
CRI													1977 \$				1977 \$		1990 \$		1990 \$		1990 \$		1990 \$		1990 \$											
5.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
10.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
15.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
20.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
25.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
30.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
35.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
40.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
45.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
50.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
55.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
60.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
65.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
70.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
75.000													5238				3275		31128		3895		77178		169791		974		24000		6411		25469		56853		113707	
[1] Materials of construction costs adjusted upward via													[MMF] =										1.70															
MATERIALS MULTIPLIER FACTOR													[EIFS] =										2.20															
[2] Adjusted upward via EQUIPMENT INSTALLATION													[OH] =										0.15															
FACTOR													[OHR] =										100															
[3] Pall ring maintenance at 25% of 1990 purchase cost.													[1] =										0.0484															
[4] Factor x Installed Capital Equipment Costs																																						
[5] Overhead Rate on Total Annual Expense, %																																						
[6] Average Annual Inflation: 1977-90																																						

(D4T)  
VOC-2.100

TABLE A-D4T  
CARBON ADSORPTION UNITS  
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

CAPITAL EXPENDITURES										TCE			
VARIABLE INPUT	NEW CHARCOAL PURCHASED		CARBON SORPTION UNITS [2]	CARBON SORPTION UNITS	TOTAL EQUIPMENT INSTALLED [3] [CAPCT]	ANNUAL FUEL OIL COSTS [5]	CHARCOAL RECYCLE COSTS	ELECTRICAL POWER COSTS	ANNUAL EXPENSE		UNLOADED TOTAL ANNUAL EXPENSE	LOADED TOTAL ANNUAL EXPENSE [4] 1990 \$ [EXPT]	
	[1] 1977\$	1990\$							1982 \$	1990 \$			1990 \$
CRI													
5.000	234	433	73577	107388	172514	4131	6133	922			11186	13982	
10.000	468	865	74354	108522	175020	4131	6133	922			11186	13982	
15.000	702	1298	75131	109656	177527	4131	6133	922			11186	13982	
20.000	936	1730	75908	110790	180033	4131	6133	922			11186	13982	
25.000	1170	2163	76685	111924	182540	4131	6133	922			11186	13982	
30.000	1404	2596	77462	113058	185046	4131	6133	922			11186	13982	
35.000	1638	3028	78238	114192	187553	4131	6133	922			11186	13982	
40.000	1872	3461	79015	115326	190059	4131	6133	922			11186	13982	
45.000	2106	3893	79792	116460	192566	4131	6133	922			11186	13982	
50.000	2340	4326	80569	117594	195072	4131	6133	922			11186	13982	
55.000	2574	4759	81346	118728	197579	4131	6133	922			11186	13982	
60.000	2808	5191	82123	119862	200085	4131	6133	922			11186	13982	
65.000	3042	5624	82900	120996	202591	4131	6133	922			11186	13982	
70.000	3276	6056	83677	122130	205098	4131	6133	922			11186	13982	
75.000	3510	6489	84454	123264	207604	4131	6133	922			11186	13982	

[DST]  
VOC-2.100

TABLE A-D5T  
CATALYTIC INCINERATION UNIT  
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

CAPITAL EXPENDITURES		* TOTAL EQUIPMENT INSTALLED		* ANNUAL EXPENSE		* LOADED TOTAL ANNUAL EXPENSE [2]	
VARIABLE INPUT		* TOTAL EQUIPMENT INSTALLED [1]		* ANNUAL EXPENSE		* LOADED TOTAL ANNUAL EXPENSE [2]	
UNIT COST	1979 \$	UNIT COST	1990 \$	ANNUAL FUEL OIL COSTS	ANNUAL ELECTRICAL POWER COSTS	ANNUAL CATALYST COST	TOTAL 1990 \$
CRI	1979 \$	UNIT COST	1990 \$	1990 \$	1990 \$	1990 \$	1990 \$
5.000	27649	46502	74403	115664	922	3293	119879
10.000	27649	46502	74403	115664	922	3293	119879
15.000	27649	46502	74403	115664	922	3293	119879
20.000	27649	46502	74403	115664	922	3293	119879
25.000	27649	46502	74403	115664	922	3293	119879
30.000	27649	46502	74403	115664	922	3293	119879
35.000	27649	46502	74403	115664	922	3293	119879
40.000	27649	46502	74403	115664	922	3293	119879
45.000	27649	46502	74403	115664	922	3293	119879
50.000	27649	46502	74403	115664	922	3293	119879
55.000	27649	46502	74403	115664	922	3293	119879
60.000	27649	46502	74403	115664	922	3293	119879
65.000	27649	46502	74403	115664	922	3293	119879
70.000	27649	46502	74403	115664	922	3293	119879
75.000	27649	46502	74403	115664	922	3293	119879

[1] Using Equipment Installation Factor (EIF) as shown in Table 1.

[2] Overhead at 25% of total annual expense. The primary burden of the overhead is placed on the packed column stripper.

(D6T)  
VOC-2.100

TABLE A-D6T  
COMBINED EQUIPMENT SYSTEMS  
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

VARIABLE INPUT	TCE											
	PACKED STRIPPER			CARBON SORPTION			PACKED STRIPPER & CARBON SORPTION			CATALYSIS UNIT		
	PACKED STRIPPER			CARBON SORPTION			PACKED STRIPPER & CARBON SORPTION			CATALYSIS UNIT		
	TOTAL FIXED CAPITAL	TOTAL ANNUAL EXPENSE	1990 \$ {CAPST}	TOTAL FIXED CAPITAL	TOTAL ANNUAL EXPENSE	1990 \$ {CAPCT}	TOTAL FIXED CAPITAL	TOTAL ANNUAL EXPENSE	1990 \$ {EXPCAT}	TOTAL FIXED CAPITAL	TOTAL ANNUAL EXPENSE	1990 \$ {EXPCATT}
CRI	169791	113707	169791	172514	13982	172514	169791	113707	169791	169791	113707	169791
5.000	169791	113707	169791	175020	13982	175020	169791	113707	169791	169791	113707	169791
10.000	169791	113707	169791	177527	13982	177527	169791	113707	169791	169791	113707	169791
15.000	169791	113707	169791	180033	13982	180033	169791	113707	169791	169791	113707	169791
20.000	169791	113707	169791	182540	13982	182540	169791	113707	169791	169791	113707	169791
25.000	169791	113707	169791	185046	13982	185046	169791	113707	169791	169791	113707	169791
30.000	169791	113707	169791	187553	13982	187553	169791	113707	169791	169791	113707	169791
35.000	169791	113707	169791	190059	13982	190059	169791	113707	169791	169791	113707	169791
40.000	169791	113707	169791	192566	13982	192566	169791	113707	169791	169791	113707	169791
45.000	169791	113707	169791	195072	13982	195072	169791	113707	169791	169791	113707	169791
50.000	169791	113707	169791	197579	13982	197579	169791	113707	169791	169791	113707	169791
55.000	169791	113707	169791	200085	13982	200085	169791	113707	169791	169791	113707	169791
60.000	169791	113707	169791	202591	13982	202591	169791	113707	169791	169791	113707	169791
65.000	169791	113707	169791	205098	13982	205098	169791	113707	169791	169791	113707	169791
70.000	169791	113707	169791	207604	13982	207604	169791	113707	169791	169791	113707	169791
75.000	169791	113707	169791				169791	113707	169791	169791	113707	169791

Compare with Table D7T, which is for the rotary stripper. In D7T, the two columns for the packed stripper are replaced by calculation of the fixed capital and the annual [non-capital] expense for the rotary stripper.

The capital and expense figures for the carbon adsorption and the catalytic incineration are identical in D6T and D7T, however.

TABLE A-D7T  
COMBINED EQUIPMENT SYSTEMS  
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

## TCE

VARIABLE INPUT	ROTARY STRIPPER (1) 1990 \$	FANS, PUMPS, MOTORS (2) 1990 \$	ROTARY STRIPPER			CARBON SORPTION			ROTARY STRIPPER & CARBON SORPTION			CATALYSIS UNIT			ROTARY STRIPPER & CATALYSIS UNIT		
			TOTAL FIXED CAPITAL (3) 1990 \$	TOTAL ANNUAL EXPENSE (4) 1990 \$	TOTAL FIXED CAPITAL (5) 1990 \$	TOTAL ANNUAL EXPENSE (5) 1990 \$	COMBINED FIXED CAPITAL (5) 1990 \$	COMBINED EXPENSE (5) 1990 \$				TOTAL FIXED CAPITAL (5) 1990 \$	TOTAL ANNUAL EXPENSE (5) 1990 \$	COMBINED FIXED CAPITAL (5) 1990 \$			
CRI			[CAPRT]	[EXPT]	[CAPCT]	[EXPT]						[CAPCATT]	[EXPCATT]				
5.000	153043	17027	272112	126529	172514	13982	444626	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
10.000	153043	17027	272112	126529	175020	13982	447133	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
15.000	153043	17027	272112	126529	177527	13982	449639	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
20.000	153043	17027	272112	126529	180033	13982	452146	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
25.000	153043	17027	272112	126529	182540	13982	454652	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
30.000	153043	17027	272112	126529	185046	13982	457159	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
35.000	153043	17027	272112	126529	187553	13982	459665	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
40.000	153043	17027	272112	126529	190059	13982	462172	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
45.000	153043	17027	272112	126529	192566	13982	464678	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
50.000	153043	17027	272112	126529	195072	13982	467184	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
55.000	153043	17027	272112	126529	197579	13982	469691	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
60.000	153043	17027	272112	126529	200085	13982	472197	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
65.000	153043	17027	272112	126529	202591	13982	474704	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
70.000	153043	17027	272112	126529	205098	13982	477210	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378
75.000	153043	17027	272112	126529	207604	13982	479717	140512	74403	149848	346516	74403	149848	346516	276378	276378	276378

(1) Based upon a Cost/Capacity scaling factor = 0.304

(2) The purchased equipment cost includes one full charge of packing materials. It also provides for stainless steel construction materials.

(3) Uses the values previously calculated for the packed stripper water pump and air fans. Then double to allow for additional power to drive the rotors of the rotary stripper.

(4) Sum of two preceding columns. Equipment installation factor [EIFC] = 1.60 which is the same factor used for the carbon adsorption and the catalytic incineration units.

(5) Uses values from the packed stripper, except for the addition of extra electrical power to handle the rotational units. See (2) above.

(5) Identical to values already calculated for the carbon adsorption and for the catalytic incineration units, at corresponding operating conditions.

NOTE: Data for rotary stripper are calculated in this table. Data for carbon adsorption and catalytic incineration units are copied from earlier tables.

## APPENDIX B

### OPERATING LIFETIME FINANCIAL ANALYSIS

#### VOC-2300

The following eight tables make up spreadsheet VOC-2.300 written in MULTIPLAN 2.01. The file may be exported upward into MP 3.0 or MP 4.0 without difficulty. Table B-1 is for inputs to the construction phase, and Table B-4 is for inputs to the operating lifetime phase. For the analyses in this report, the construction phase is assumed to be zero years, so that Tables B-1 and B-4 are essentially identical. Table B-8 contains the output information, in terms of lifetime current dollars cost per 1000 gallons of groundwater processed. Annual adjustments for inflation are included, using the input inflation projection shown in Table B-4. Three copies of Table B-8 are included here, to illustrate output summaries for a packed stripper alone, stripper plus carbon adsorption off-gas treatment, and stripper plus catalytic incineration off-gas treatment. The analyses are handled as 100 percent debt financing to simulate a government-owned and operated activity. At 100 percent debt financing and at zero salvage on the capital equipment, the lifetime processing costs per 1000 gallons of water should be identical for a cash flow analysis and for a depreciation analysis. This identity is shown in Table D-8. Further details will be found in the related body of the text, as well as in a separate "user/operator manual" for the spreadsheet.

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TABLE B-1  
INITIAL COST ESTIMATES AND OTHER  
KEY PARAMETERS

INPUT ITEM	NAME	INPUT
BASE YEAR	[Y]	= 1990
CURRENCY UNITS (1E+3, 1E+6, etc.)	[CU]	= 1.0E+06
NUMBER OF CONSTRUCTION YEARS TO STARTUP	[N]	= 0
F INITIAL FIXED CAPITAL, F	[F]	= 0.632401
CONTINGENCY ADD-ON ADJUSTMENT	[AF]	= 0.00
FC INITIAL FC, PLUS CONTINGENCY	C----> [FC]	= 0.632401
W INITIAL WORKING CAPITAL, W	[W]	= 0.000000
CONTINGENCY ADD-ON ADJUSTMENT	[AW]	= 0.00
WC INITIAL WC, PLUS CONTINGENCY	C----> [WC]	= 0.000000
E INITIAL ANNUAL EXPENSE, E	[E]	= 0.581721
CONTINGENCY ADD-ON ADJUSTMENT	[AE]	= 0
EC INITIAL EC, PLUS CONTINGENCY	C----> [EC]	= 0.581721
FIRST YEAR FC INPUT FRACTION	[f1]	= 1.00
SECOND YEAR FC INPUT FRACTION	[f2]	= 0.00
THIRD YEAR FC INPUT FRACTION	[f3]	= 0.00
FOURTH YEAR FC INPUT FRACTION	[f4]	= 0.00
FIFTH YEAR FC INPUT FRACTION	[f5]	= 0.00
{ NOTE: f1 thru f5 must add to 1.00 }		
DEBT FRACTION [MAX = 1.000]	[D]	= 1.000
ANNUAL INFLATION DURING CONSTRUCTION	[IF]	= 0.0484
REAL INTEREST DURING CONSTRUCTION	[RIR]	= 0.0500
INTEREST DURING CONSTRUCTION	C----> [IN]	= 0.0984

C----> These are COMPUTED items. Others inserted as appropriate.

[ ] Means a NAMED cell, range, or area, at its initially named location.

{ } Means an item copied from the earlier named cell or range, at an earlier location.

[PF], PF ----> PRINT FILE MACRO, FOR ALL TABLES IN SPREADSHEET



TABLE B-2

## INTERIM INFORMATION

BEFORE & AFTER INFLATION ADJUSTMENTS, &  
WITH DEBT FRACTION ADJUSTMENT AS WELL,  
BUT ... WITH NO INTEREST INCLUDED.  
=====

CALENDAR YEAR [CALY]	CONSTRUCTION YEAR [CONY]	YEARS OF INFLATION [INFY]	ANNUAL * INPUTS REQUIRED [AIR]	INFLATED ANNUAL ** INPUTS REQUIRED [IAIR]	DEBT *** PORTION [DP]	EQUITY *** PORTION [EP]
1990	1	0	0.6324	0.6324	0.6324	0.0000
1991	2	1	0.0000	0.0000	0.0000	0.0000
1992	3	2	0.0000	0.0000	0.0000	0.0000
1993	4	3	0.0000	0.0000	0.0000	0.0000
1994	5	4	0.0000	0.0000	0.0000	0.0000
1995	6	5	0.0000	0.0000	0.0000	0.0000
CONSTRUCTION PERIOD TOTALS =			0.6324	0.6324	0.6324	0.0000

DEBT FRACTION VERIFICATION = 1

\* UNINFLATED DISTRIBUTION OF THE INITIAL FCC ESTIMATE  
 \*\* INFLATION ADJUSTED ANNUAL DISTRIBUTION OF THE INITIAL FCC ESTIMATE  
 \*\*\*COMPARE THESE TWO COLUMNS WITH DISTRIBUTION CALCULATED IN THE  
 FOLLOWING TABLE C. NOTE - - THAT IN THIS TABLE B THERE HAS BEEN NO  
 INTEREST CALCULATED ON DEBT, WHICH IS DONE IN TABLE C.

ALSO NOTE THAT SOME INTERNAL SUMMATION CHECKS ARE PROVIDED ABOVE.

READ NOTES BELOW

NOTE THAT TABLE B ABOVE IS FOR INTERIM INFORMATION DISPLAY ONLY, AND COULD  
 READILY BE CONSOLIDATED INTO TABLE C.

TABLE B-3

## CONSTRUCTION YEARS: ANALYSIS OF FIXED CAPITAL STRUCTURE

ANNUAL REQUIRED INPUTS						
CALENDAR YEAR	CONST. YEAR	ANNUAL TOTALS	EQUITY PORTION	DEBT PORTION	CUMULATIVE TOTAL	CUMULATIVE DEBT
1990	1	0.632401	0.632401	0.000000	0.632401	0.000000
1991	2	0.000000	0.000000	0.000000	0.000000	0.000000
1992	3	0.000000	0.000000	0.000000	0.000000	0.000000
1993	4	0.000000	0.000000	0.000000	0.000000	0.000000
1994	5	0.000000	0.000000	0.000000	0.000000	0.000000
1995	6	0.000000	0.000000	0.000000	0.000000	0.000000
-----						
COLUMN		0.63240	0.63240	0.00000		
TOTALS		0.63240	0.63240	0.00000	0.00000	
-----						
D + E			<<----- NAME OF VALUE BELOW			
TOTAL----->			(FCC)	RESULTING DEBT FRACTION AT START UP =		
			0.632401	0		
-----						

THE COLUMN TOTALS FOR 'ANNUAL REQUIRED INPUTS' GIVE (1) THE TOTAL FCC ESTIMATE IN START UP YEAR DOLLARS, FOR THE INPUTS SPECIFIED IN TABLE A, AND (2) THE DEBT AND EQUITY PORTIONS FOR THE DEBT FRACTION ALSO SPECIFIED IN TABLE A. ALL OF THE DOLLAR VALUES HAVE BEEN ADJUSTED FOR THE STIPULATED INTEREST AND INFLATION DURING THE CONSTRUCTION YEARS ... THUS WE HAVE THE FCC ESTIMATE IN START UP YEAR DOLLARS THAT WILL BE USED DURING SUBSEQUENT OPERATING YEARS ANALYSIS. EMPHASIS...WE DO HOLD THE STATED DEBT FRACTION CONSTANT DURING THE CONSTRUCTION YEARS.

AS IN MOST TABLES OF THIS SPREAD SHEET, CLOSURE CHECKS ARE PROVIDED.  
NOTE ALSO THAT THE FCC IS A NAMED VARIABLE AS INDICATED IN THE TABLE FOOTNOTES.

NOTE: THE LAST YEAR IN THE ABOVE TABLE IS NOT A CONSTRUCTION YEAR, BUT ACTUALLY IS THE YEAR OPERATIONS START. IT IS INCLUDED SO THAT WE HAVE A PLACE TO DISPLAY AND USE THE ACCRUED BUT UNPAID INTEREST AT THE END OF THE CONSTRUCTION PERIOD.

ALSO...REMEMBER THAT THIS CONSTRUCTION PERIOD SPREADSHEET IS SET UP SO THAT WE ARE ABLE TO HOLD THE SPECIFIED DEBT FRACTION CONSTANT.

TABLE B-4

## INPUT TABLE FOR OPERATING YEARS, STARTING --- 1990

NUMBER OF OPERATING YEARS	[M] =	20
FIXED CAPITAL COST ESTIMATE AT START UP	{FCC}	= 0.632401
SALVAGE FRACTION	[SF]	= 0.00
SALVAGE AMOUNT	C----> [SA]	= 0.000000
WORKING CAPITAL FACTOR	[WCF]	= 0.00
INITIAL YEAR WORKING CAPITAL COST ESTIMATE	C----> [WCC]	= 0.000000
NON-CAPITAL EXPENSE FACTOR	[EXPF]	= 0.000
INITIAL YEAR NON-CAPITAL EXPENSE EST.	C----> [EXP]	= 0.581721
OPERATING YEARS DEBT FRACTION *	[DO]	= 1.000
INFLATION RATE DURING OPERATIONS *	[IFO]	= 0.0484
REAL INTEREST RATE DURING OPERATIONS *	[RIRO]	= 0.0500
INTEREST RATE DURING OPERATIONS	C----> [INO]	= 0.0984
TAX RATE ON PROFITS	[T]	= 0.00
PRODUCTION FACTORS: L = 1.00 FOR 365 DAYS PER YEAR		
FIRST YEAR FACTOR	[L1]	= 0.85
SECOND YEAR FACTOR	[L2]	= 0.85
THIRD YEAR FACTOR	[L3]	= 0.85
FOURTH YEAR FACTOR **	[L4]	= 0.85
GROUND WATER PUMPING RATE, gal/min	[WPR]	= 1500
WATER ANNUAL PROCESSING (FOR L = 1) in gal/yr	C----> [AWPR]	= 7.884E+08
NUMBER OF DEPRECIATION YEARS ***	[DY]	= 20
(STRAIGHT LINE METHOD)		

C----&gt; These are COMPUTED values...don't set anything here.

{ } DON'T SET NEW VALUE...COPIED FROM PREVIOUS LOCATIONS.

\* May set equal to values from Table-A, OR... may set new values here.

\*\* L4 value continues for all subsequent years.

\*\*\* Normally set = M, the total operating lifetime.

ALL OTHER VALUES MAY BE INSERTED AS APPROPRIATE.

TABLE B-5  
ANNUAL WATER PROCESSING LEVELS

OPERATING YEAR {OY}	BASE CASE PROCESSING gal/year {AWPR}	PROCESSING LOAD FACTORS {fl, etc.}	ACTUAL PROCESSING gal/year {AP}
1	7.884E+08	0.85	6.701E+08
2	7.884E+08	0.85	6.701E+08
3	7.884E+08	0.85	6.701E+08
4	7.884E+08	0.85	6.701E+08
5	7.884E+08	0.85	6.701E+08
6	7.884E+08	0.85	6.701E+08
7	7.884E+08	0.85	6.701E+08
8	7.884E+08	0.85	6.701E+08
9	7.884E+08	0.85	6.701E+08
10	7.884E+08	0.85	6.701E+08
11	7.884E+08	0.85	6.701E+08
12	7.884E+08	0.85	6.701E+08
13	7.884E+08	0.85	6.701E+08
14	7.884E+08	0.85	6.701E+08
15	7.884E+08	0.85	6.701E+08
16	7.884E+08	0.85	6.701E+08
17	7.884E+08	0.85	6.701E+08
18	7.884E+08	0.85	6.701E+08
19	7.884E+08	0.85	6.701E+08
20	7.884E+08	0.85	6.701E+08
LIFETIME PROCESSING =		{SUMW} = 1.340E+10	
in gallons			

[illegible]

TABLE B-7

## DEPRECIATION BASED COST ANALYSIS

OPERATING YEAR {OY}	ANNUAL NON-CAP EXPENSE {ANE}	ANNUAL INTEREST ON FCC {FCCI}	ANNUAL INTEREST ON WCC {IWCC}	ANNUAL DEPRECIATION {AD}	EXPENSE FOR TAX PURPOSES {EFTP}
1	0.58172	0.06223	0.00000	0.03162	0.67557
2	0.60988	0.06112	0.00000	0.03162	0.70262
3	0.63939	0.05991	0.00000	0.03162	0.73092
4	0.67034	0.05857	0.00000	0.03162	0.76053
5	0.70279	0.05711	0.00000	0.03162	0.79151
6	0.73680	0.05550	0.00000	0.03162	0.82392
7	0.77246	0.05373	0.00000	0.03162	0.85781
8	0.80985	0.05178	0.00000	0.03162	0.89325
9	0.84905	0.04965	0.00000	0.03162	0.93031
10	0.89014	0.04730	0.00000	0.03162	0.96906
11	0.93322	0.04473	0.00000	0.03162	1.00957
12	0.97839	0.04190	0.00000	0.03162	1.05191
13	1.02574	0.03880	0.00000	0.03162	1.09616
14	1.07539	0.03538	0.00000	0.03162	1.14239
15	1.12744	0.03164	0.00000	0.03162	1.19069
16	1.18201	0.02752	0.00000	0.03162	1.24115
17	1.23922	0.02300	0.00000	0.03162	1.29383
18	1.29919	0.01803	0.00000	0.03162	1.34884
19	1.36207	0.01257	0.00000	0.03162	1.40627
20	1.42800	0.00658	0.00000	0.03162	1.46620
21					
[SUMEXP]	-----> 19.75013	[SUMD]	0.63240		20.3825
					[SEFTP]
		TEST, (1 - SF)*FCC =	0.63240		

## USING STRAIGHT LINE DEPRECIATION

SALVAGE FRACTION [SF] = 0  
NUMBER OF DEPRECIATION YEARS [DY] = 20  
[D] = 1.000 [INO] = 0.098  
[DO] = 1.000 [IFO] = 0.048

TABLE B-8

[A]	DOLLAR COST PER 1,000 GALLONS, BASED UPON CASHFLOW ANALYSIS = 1.5208
	DOLLAR COST PER 1,000 GALLONS, CONTRIBUTION OF NON-CAPITAL ANNUAL EXPENSES = 1.4736
	DOLLAR COST PER 1,000 GALLONS, CONTRIBUTION OF FIXED CAPITAL DEPRECIATION = 0.0472
[B]	CONSOLIDATED DOLLAR COST PER 1,000 GALLONS, AS SUM OF CAPITAL AND NON-CAPITAL COSTS = 1.5208

NOTE: For construction and operating lifetime debt fractions = 1.000  
or zero equity, the costs per 1,000 gallons of water process as shown in [A] and [B]  
should be identical.

NOTE: THESE ARE BASED UPON LIFETIME INFLATION ADJUSTMENTS, STARTING WITH INITIAL ESTIMATES,  
AND THUS ARE CURRENT DOLLAR AVERAGES FOR THE OPERATING LIFETIME.

# CONSTRUCTION PHASE

CU = 1.00E+06  
N = 0  
F = 0.6324  
AF = 0.0000  
FC = 0.6324  
f1 = 1.00  
f2 = 0.00  
f3 = 0.00  
f4 = 0.00  
f5 = 0.00  
D = 1.00  
IF = 0.0484  
RIR = 0.0500  
IN = 0.0984  
  
WPR = 1500  
AWPR = 7.884E+08

# OPERATIONS PHASE

M = 20  
FCC = 0.6324  
SF = 0.0000  
SA = 0.0000  
WCF = 0.0000  
WCC = 0.0000  
EXPF = 0.0000  
EXP = 0.5817  
DO = 1.00  
IFO = 0.0484  
RIRO = 0.0500  
INO = 0.0984  
T = 0.000  
L1 = 0.850  
L2 = 0.850  
L3 = 0.850  
L4 = 0.850  
DY = 20

## APPENDIX C

### DATA SETS USED FOR ANALYSIS AND EVALUATION

This appendix contains a data organization Table C-1 and examples from the 32 data sets used for analysis and evaluation in this report. The 32 data sets were the basis for preparation of graphs contained in the main body of this report. The tables and graphs present a "cost" in terms of dollars per 1000 gallons of water processed over a 20-year operating lifetime. This lifetime cost evaluation was done with spreadsheet VOC-2.300, and with data outputs from VOC-2.100 and VOC-2.200.

The notation "S.1" etc. in Table C-1 provides linking access to a separately bound set of wide carriage computer printouts. That separately bound printout set contains more data than actually used for analyses in this report.

The cost estimating for this report may have an uncertainty range of approximately  $\pm 30$  percent. Thus, the estimating "accuracy" would not warrant the five significant figures used in the following tables. That precision is used, however, in order to take advantage of the sensitivity analysis precision available through the computer simulation spreadsheets used for this project.

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TABLE C-1. ORGANIZATIONAL CHART FOR DATA ANALYSIS

Variables used for sensitivity analyses	Method A-1 VOC-2,100						Method A-2 VOC-2,100			Method B-1 VOC-2,200	Method B-2 VOC-2,200
	Packed Stripper	Packed Stripper	Rotary Stripper	Rotary Stripper	Rotary Stripper	Packed Stripper	Packed Stripper	Rotary Stripper	Rotary Stripper	Packed Stripper	Packed Stripper
	Benzene	TCE	Benzene	TCE	TCE	Benzene	TCE	Benzene	TCE	TCE	Benzene
WGM = 100-1500 gpm	S-1	S-3	S-2	S-4	S-4	S-27		S-28		S-49	S-52
S = 2-10	S-5	S-7	S-6	S-8	S-8	S-29		S-30		S-50	S-53
FF = 0.1-0.9	S-9	S-11	S-10	S-12	S-12	S-31		S-32		S-51	S-54
EIFS,EIFC = 1.2-2.6		S-13									
EIFS,EIFC = 2.4-5.2		S-13									
WGM = 100-1500 gpm* EIF = 4.83		S-15									
CUF = 0.990-0.999 PPBI = 10,000		S-17									
CUF = 0.990-0.999** PPBI = 5,000		S-19									
OHR = 30-100%		S-21									
CRI = 7-75 days		S-23									
CUF - Special Case***		S-25			S-26						

TABLE C-1. ORGANIZATIONAL CHART FOR DATA ANALYSIS (CONCLUDED)

Method A-1 reflects the original input-output specifications of August 31, 1989 -- with the concentration of both contaminants in the groundwater = 10 ppm.....For Method A-2, the concentration of Benzene in the groundwater was dropped to 0.1 ppm. For both of the methods, Thomas' cost estimating methods were used.

For Methods B-1 and B-2, the cost estimating methods were modified to use EPA methods, as discussed in the text. For B-1, the TCE groundwater concentration = 10 ppm. For B-2 the Benzene groundwater concentration = 0.1 ppm.

All inputs to the design and cost estimating spreadsheets are those shown in Tables 1 and 2 of the text, with the following exceptions.

- Fixed value of the Equipment Installation Factor = 4.83.
- Concentration of the key contaminants [BZ and TCE] = 5,000 ppb.
- The Special Case requested by USAF via ORNL on August 31, 1989 uses the following inputs:

Water flow rate	= 200	Pall Ring Packing, 5/8 inch
Temperature, C	= 10	Rotary Stripper, TCE only
S	= 8	Clean Up Fraction = 99% & 99.9%
FF	= 0.4	PPBI = 5,000

As indicated by the organizational table on page 267, and the other data in this chapter, the special case requested by USAF was expanded to include further information.

The above organizational chart provides information regarding the data sets which were run and evaluated for purposes of this report. The set of output data tables run and delivered to ORNL in computer wide carriage printout form is larger than that shown on the organizational chart, and could be used to do additional interpretive analyses.

TABLE C-2. PROCESSING COSTS PER 1000 GALLONS WATER - ANNUALLY INFLATED CURRENT DOLLARS

PACKED STRIPPER - BENZENE

Variable [WGM]	Stripper Alone			Stripper Plus Carbon			Stripper Plus Catalysis		
	Fixed Capital	Expense	Total	Fixed Capital	Expense	Total	Fixed Capital	Expense	Total
100	0.1095	3.0787	3.1882	0.3840	9.2762	9.6602	0.1084	4.7162	4.9012
200	0.0692	1.7503	1.8195	0.2484	7.6029	7.8513	0.1084	3.3381	3.4465
300	0.0532	1.2879	1.3411	0.2007	6.8899	7.0906	0.0804	2.8589	2.9393
400	0.0443	1.0419	1.0862	0.1760	6.4240	6.6000	0.0654	2.6042	2.6696
500	0.0386	0.8890	0.9276	0.1607	6.0693	6.2300	0.0561	2.4461	2.5022
600	0.0345	0.7882	0.8227	0.1502	5.7801	5.9303	0.0496	2.3416	2.3912
700	0.0314	0.7102	0.7416	0.1426	5.5253	5.6679	0.0448	2.2611	2.3059
800	0.0289	0.6507	0.6796	0.1368	5.2993	5.4361	0.0410	2.1995	2.2405
900	0.0270	0.6061	0.6331	0.1322	5.0979	5.2301	0.0381	2.1534	2.1915
1000	0.0254	0.5672	0.5926	0.1285	4.9112	5.0397	0.0356	2.1132	2.1488
1100	0.0240	0.5373	0.5613	0.1254	4.7421	4.8675	0.0336	2.0822	2.1158
1200	0.0228	0.5122	0.5350	0.1227	4.5861	4.7088	0.0319	2.0562	2.0881
1300	0.0218	0.4879	0.5097	0.1205	4.4389	4.5594	0.0304	2.0311	2.0615
1400	0.0209	0.4693	0.4902	0.1185	4.3050	4.4235	0.0291	2.0118	2.0409
1500	0.0201	0.4506	0.4707	0.1168	4.1784	4.2952	0.0280	1.9926	2.0206

Note: "S1" is related to the organizational Table C.1.

TABLE C-3. PROCESSING COSTS PER 1000 GALLONS WATER - ANNUALLY  
INFLATED CURRENT DOLLARS - BASE YEAR = 1990

ROTARY STRIPPER - BENZENE

	Stripper Alone	Stripper Plus Carbon	Stripper Plus Catalysis
Variable [S]	Total	Total	Total
2	1.1855	5.6229	2.0153
3	1.1044	6.1415	2.3103
4	1.0823	6.6137	2.6911
5	1.0761	7.0225	3.0905
6	1.0666	7.3563	3.4725
7	1.0723	7.6863	3.8911
8	1.0699	7.9599	4.2870
9	1.0683	8.2092	4.6849
10	1.0698	8.4458	5.0916

TABLE C-4. PROCESSING COSTS PER 1000 GALLONS WATER - ANNUALLY  
INFLATED CURRENT DOLLARS - BASE YEAR = 1990

ROTARY STRIPPER - TCE

	Stripper Alone	Stripper Plus Carbon	Stripper Plus Catalysis
Variable [FF]	Total	Total	Total
0.1	1.1403	2.3174	2.2612
0.2	1.0816	2.2592	2.2030
0.3	1.0655	2.2454	2.1892
0.4	1.0623	2.2477	2.1915
0.5	1.0638	2.2598	2.2036
0.6	1.0536	2.2620	2.2058
0.7	1.0321	2.2700	2.2139
0.8	0.9722	2.1997	2.1435
0.9	0.9101	2.1261	2.0699